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August 1962

MACHINING OF REFRACTORY MATERIALS

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METCUT RESEARCH ASSOCIATES INC.
CINCINNATI, OHIO

Contract: AF 33(600)-42349
ASD Project: 7-532a

Phase II Technical Engineering Report
1 May 1962 - 31 July 1962

Machining studies were performed on pressed and sintered, forged and resintered, and arc cast unalloyed tungsten; D-31 columbium, 90Ta-10W alloy; silica reinforced phenolic resin; solid zirconium oxide; and zirconium and aluminum oxide coatings. The investigation consisted of face milling, end milling, drilling and tapping studies on tungsten and D-31 columbium; turning, face milling, drilling and tapping on silica reinforced phenolic resin; grinding of solid and flame sprayed zirconium and aluminum oxide coatings; and turning, face milling, end milling, drilling, reaming, tapping and grinding on the 90Ta-10W alloy.

FABRICATIONS BRANCH
MANUFACTURING TECHNOLOGY LABORATORY

Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

ABSTRACT - SUMMARY
Phase II Technical Engineering Report

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et al
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Machining studies were performed on pressed and sintered, forged and resintered, and arc cast unalloyed tungsten; D-31 columbium, 90Ta-10W alloy; silica reinforced phenolic resin; solid zirconium oxide; and zirconium and aluminum oxide coatings. The investigation consisted of face milling, end milling, drilling and tapping studies on tungsten and D-31 columbium; turning, face milling, drilling and tapping on silica reinforced phenolic resin; grinding of solid and flame sprayed zirconium and aluminum oxide coatings; and turning, face milling, end milling, drilling, reaming, tapping and grinding on the 90Ta-10W alloy.

In face milling and end mill slotting forged and resintered tungsten, best tool life was obtained when machining the workpiece at room temperature. However, in peripheral end milling pressed and sintered tungsten, tool life was increased appreciably when the workpiece temperature was increased to 800°F.

Drilling tests performed at room temperature with grade 883 (C-2) solid carbide twist drills operating at 150 feet/minute with a feed of .002 inches/revolution showed that 15 holes could be drilled in forged and resintered tungsten 96% density, 35 R_c. With the same drilling conditions, 12 holes were drilled in 93% density pressed and sintered tungsten, 34 R_c; and 9 holes in arc cast tungsten 99% density, 31 R_c.

A tap life of 14 holes was obtained in pressed and sintered tungsten, 95% density, 34 R_c, when tapping at 5.3 feet/minute with workpiece temperatures of 400°F to 800°F. A special stub tap was used for these tests.

In surface grinding pressed and sintered tungsten 95% density, 34 R_c, minimum distortion and residual stress is produced in the workpiece when using low wheel speeds, 2000 to 3000 feet/minute with a soluble oil grinding fluid, a grade "N" hardness wheel and a down feed of .001 inches/pass.

In face milling D-31 columbium, a tool life of 90 inches/tooth work travel was obtained using a grade K-6 (C-2) carbide cutter operating at 142 feet/minute with a feed of .010 inches/tooth.

Silica fiber reinforced phenolic resin cannot be machined economically with high speed steel tools. Because of the abrasiveness of this material, carbide tools should be used.

Grinding ratios of the order of 5 to 10 were obtained in surface grinding tests performed on 99% dense solid zirconium oxide.

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NOTICES

FOREWARD

This Phase II Interim Technical Progress Report covers the work performed under Contract AF 33(600)-42349 from 1 May 1962 to 31 July 1962. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio was initiated under ASD Manufacturing Technology Laboratory Project 7-532a, "Machining of Refractory Materials". It is being administered under the direction of Mr. Robert T. Jameson of the Fabrications Branch (ASRCTF), Manufacturing Technology Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

Mr. Norman Zlatin, Director of Machinability Research at Metcut, is the engineer in charge of this program. Others who have cooperated in the investigation reported herein and preparation of the report were Mr. J. V. Gould, Project Engineer, and Dr. Michael Field, Research Director. This project has been given the Metcut Research Internal No. 470-3300.

The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and improve the quality and efficiency of fabrication of aircraft, missiles, and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout industry, thereby reducing costs and giving "MORE AIR FORCE PER DOLLAR".

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional development required on this or other subjects will be appreciated.

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PUBLICATION REVIEW

Approved by: ______________________
Norman Zlatin
Director, Machinability Research

Approved by: ______________________
Michael Field
Research Director

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1. INTRODUCTION

The purpose of this program is to investigate and evaluate the machining characteristics of the refractory materials, selected high temperature alloys, and high strength steels of importance to the aerospace industry.

The machining research on the various alloys is being carried out under Phase II of the subject contract, and this report presents the results obtained during the period of 1 May 1962 to 31 July 1962.

Machining studies have been made on pressed and sintered, forged and re-sintered and arc cast tungsten; D-31 columbium, 90Ta-10W alloy, Silica fiber reinforced phenolic resin, solid zirconium oxide, and flame sprayed zirconium oxide and aluminum oxide coatings. The machining test data obtained for these materials is presented in graphical and tabular form to show the effect of machining variables on tool life, and their relationship between the machining variables.

2. MATERIALS USED IN MACHINING TESTS

The materials used in the machining tests were as follows:

Unalloyed Tungsten, Pressed and Sintered, 95% theoretical density	34 R_c
Unalloyed Tungsten, Forged and Resintered, 96% theoretical density	35 R_c
Unalloyed Tungsten, Arc Cast, 99% theoretical density	31 R_c
D-31 Columbium	207-217 BHN
90Ta-10W Alloy	207 BHN
Silica Fiber Reinforced Phenolic Resin	
Solid Zirconium Oxide 70% and 99% theoretical density	
Flame Sprayed Zirconium Oxide and Aluminum Oxide Coatings	

2.1 Chemical Composition

The nominal chemical compositions of the alloys used in the machining tests were as follows:

	C	O_2	Mn	Si	Mo	Co	W
Unalloyed Tungsten	.005	.045	.001	.01	.01	.01	Bal.

Unalloyed Tungsten — Trace: Ni, Fe, Cb, V, N, Ti, Al

	Ti	Mo	Cb
D-31 Columbium	10.0	10.0	Bal.

	Ta	W
90Ta-10W	88.9	11.1

2.2 Heat Treatment

The pressed and sintered, forged and resintered and arc cast tungsten were not given any heat treatment. The heat treatments given the other alloys were as follows:

2.2 Heat Treatment (continued)

D-31 Columbium

	Hardness
Round Bar - extruded, stress relieved	207 BHN
Rectangular Bar - extruded, stress relieved	217 BHN

90Ta-10W

	Hardness
Round Bar - electron beam melted	207 BHN
Rectangular Bar - electron beam melted, forged	207 BHN

3. MACHINING TEST CONDITIONS

3.1 Machine Tools Used for Testing

Photographs of the lathe, milling machines, drilling machines and surface grinders used in the machinability tests were shown in ASD Interim Report 7-532a(III), dated August, 1961.

The turning tests were made on a 16" x 30" American Pacemaker lathe. This lathe is equipped with a 30 H.P. infinitely variable speed drive to provide exact cutting speed control as the bar diameter changes.

Milling tests were performed on a Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine. The machine is equipped with a cast iron flywheel to maintain a more constant speed when the interrupted cuts in face milling are encountered.

End milling tests were performed on a Cincinnati Vertical No. 2 Dial Type Milling Machine. A rotary seal is attached to the top of a hollow draw bar for applying spray mist or cutting fluid through a hole along the axis of the cutter. The machine also contains the standard integral cutting fluid system.

A Fosdick Heavy Duty 25" Box Column Upright Drill Press and a Cincinnati 16" Box Column Drill Press were used for the drilling, reaming and tapping tests. Both machines are equipped with separate infinitely variable speed drives to obtain feeds of .0001 to .025 inches per revolution. The Cincinnati drilling machine is also equipped with an infinitely variable spindle speed drive to provide exact drilling speed control.

The grinding tests were performed on a Norton 8" x 24" Hydraulic Surface Grinder. Grinding wheel speeds ranging from 1000 to 7500 surface feet per minute can be obtained on this machine by means of an infinitely variable speed spindle drive.

3.2 Turning Conditions

Turning tests were made using high speed steel, cast alloy and carbide tools.

Machine

16" x 30" American Pacemaker lathe equipped with a 30 H.P. variable speed drive.

3.2 Turning Conditions (continued)

Test Bars

Turning test bars ranged between 3" and 4" in diameter by 10" to 15" long. A surface skin cut was taken on each bar before machining tests were made to remove any surface effects from prior treatment.

Cutting Tools

Turning tests were made using throwaway type and brazed tip carbide tools and 5/8" square high speed steel and cast alloy tool bits.

Tool Materials - Carbide

A variety of carbide grades were used. The data charts give specific applications.

Tool Geometry - Carbide

Side Rake (SR)	20° to -15°
Back Rake (BR)	0° to -15°
Side Cutting Edge Angle (SCEA)	0° to 15°
End Cutting Edge Angle (ECEA)	5° to 15°
Side Relief	5° to 10°
End Relief	5° to 10°
Nose Radius (NR)	1/64" and 1/32"

Machining Conditions - Carbide

Feed: .005 in./rev. to .015 in./rev.

Depth of Cut: .030" to .100"

Cutting Fluid: Highly sulphurized oil, highly chlorinated oil, water soluble emulsions and dry.

Tool Life End Point: .015" uniform wearland or .030" localized wearland.

Tool Material - Cast Alloy and High Speed Steel Tools

Crobalt No. 2 and Stellite 98 M-2 Cast alloy tool bits

M-2, T-15 and Braecut high speed steel tool bits

3.2 Turning Conditions (continued)

Tool Geometry - Cast Alloy and High Speed Steel

Type: 5/8" square tool bits
Tool Geometry:

Side Rake	0° to 30°
Back Rake	0°
Side Cutting Edge Angle	0°
End Cutting Edge Angle	5°
Side Relief	5°
End Relief	5°
Nose Radius (NR)	1/64"

Machining Conditions - Cast Alloy and High Speed Steel Tools

Feed: .005 in./rev. to .015 in./rev.
Depth of Cut: .030" to .060"
Cutting Fluid: Highly sulphurized oil, highly chlorinated oil and water soluble emulsions.
Tool Life End Point: .030" to .060" wearland.

3.3 Face Milling Conditions

Face milling tests were made using single and multiple tooth carbide and high speed steel cutters.

Machine

A Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine was used in the face milling tests.

Test Bars

The test bars were nominally 1-1/2" to 2" thick by 4" wide by 10" long. A clean-up machining cut was made on all sides to remove any surface effects from prior treatment.

Cutters

A 4" diameter experimental cutter using clamped in 5/8" square tool bits was used as a single tooth cutter for the tool material, tool geometry, cutting speed and feed evaluation. A 5" diameter 5 tooth inserted tooth cutter was used in the multiple tooth face milling tests.

Tool Material - Carbide

A variety of carbide grades were used in the face milling tests. The data charts give specific applications.

3.3 Face Milling Conditions (continued)

Tool Geometry - Carbide

Axial Rake (AR)	10° to -10°
Radial Rake (RR)	10° to -5°
Corner Angle (CA)	45°
End Cutting Edge Angle (ECEA)	5°
Peripheral Clearance	6° to 10°

Machining Conditions - Carbide

Feed per Tooth: .003" to .010"
Depth of Cut: .030" to .060"
Width of Cut: 2"
Cutting Fluid: Soluble Oil (1:20), Highly Chlorinated Oil, Highly Sulphurized Oil and Dry
Tool Life End Point: .015" wearland on peripheral flank of cutter or .030" localized wear, whichever occurred first.

Tool Material - High Speed Steel

M-2, T-15 and Braecut high speed steel.

Tool Geometry - High Speed Steel

Axial Rake (AR)	0° to 20°
Radial Rake (RR)	0° to 30°
Corner Angle (CA)	45°
End Cutting Edge Angle (ECEA)	5°
Peripheral Clearance	10°

Machining Conditions - High Speed Steel

Feed per Tooth: .005" to .010"
Depth of Cut: .030" to .060"
Width of Cut: 1-1/2" to 2"
Cutting Fluid: Highly sulphurized oil, highly chlorinated oil and water soluble emulsions.
Tool Life End Point: .016" uniform wear or .030" localized wear, whichever occurred first.

3.4 End Milling Conditions

End milling tests were made using high speed steel cutters for producing slotting cuts. Tool life is expressed in inches of work travel to obtain a specific wearland on the tool.

Machine

A Cincinnati No. 2 Vertical Dial Type Milling Machine was used for the end milling tests.

Test Bars

The test bars were nominally 2" thick by 4" wide by 10" long. All sides were clean-up machined prior to testing to remove any surface effects from prior treatment.

Cutters - High Speed Steel

The end mills used in the tests were 3/4" and 1/2" diameter, 4 tooth, right hand spiral, right hand cut, high speed steel end mills.

Tool Materials - High Speed Steel

Type M-2, Type M-3 and Type T-15

Tool Geometry - High Speed Steel

Number of Teeth:	4
Helix Angle	30°
Radial Rake (RR)	10°
Corner Angle (CA)	45° x .060"
Peripheral Clearance	6° to 10°

Machining Conditions

Feed per Tooth: .001" to .004"
Depth of Cut: .125" to .500"
Width of Cut: 1/2" and 3/4"
Cutting Fluid: Highly Chlorinated Oil, Highly Sulphurized Oil and Water Soluble Emulsions
Tool Life End Point: .015" uniform wearland or .030" localized wear on peripheral cutting edge, whichever occurred first.

3.5 Drilling Conditions

Drilling tests were made using solid carbide, carbide tipped and high speed steel drills.

Machine

Drill life testing was done on a Cincinnati 16" Box Column Drilling Machine. This machine was equipped with an infinitely variable spindle speed and feed drive to provide exact cutting speed control and to obtain feeds of .0001 to .025 inches per revolution.

Test Samples

The drilling test samples were 1/2" thick plates cut from round and rectangular bar stock, and 1/8" and 1/16" sheet.

Drill Material - Carbide

Solid carbide, grade 883 (C-2) drills were used for the tests.

Drill Geometry

Drill Diameter: .213" (#3)
Drill Length: 2-3/4"
Point Angle: $90^{\circ}/118^{\circ}$
Clearance: 10°
Helix Angle: 20°
Point Grind: Notched

Drilling Conditions - Carbide

Feed: .0005 to .002 inches/revolution
Depth of Hole: .500 through hole and 1/8" and 1/16" through hole
Cutting Fluid: Highly Chlorinated Oil and Dry
Drill Life End Point: .030" wearland on drill margin

Drill Material - High Speed Steel

M-1, M-2, M-3, M-33 and T-15 type high speed steel drills were used in the tests.

3.5 Drilling Conditions (continued)

Drill Geometry - High Speed Steel

Drill Diameter: .213" (#3) and .250"
Drill Length: 2-1/2"
Point Angle: 90°, 118°, $90^\circ/118^\circ$, 135°, $90^\circ/135^\circ$
Helix Angle: 29°
Clearance: 7°
Point Grind: Plain and split

Drilling Conditions - High Speed Steel

Feed: .002 to .005 inches/revolution
Depth of Hole: .500" through hole
Cutting Fluid: Highly Sulphurized Oil, Highly Chlorinated Oil and Water Soluble Emulsions.

3.6 Reaming Conditions

Reaming tests were made using high speed steel chucking reamers.

Machine

The reaming tests were made on a Cincinnati 16" Box Column Drilling Machine.

Test Samples

The reaming tests were made on 1/2" thick slugs on which drilling studies had previously been made.

Reamer Material

M-2 type high speed steel.

Reamer Geometry

Type: Straight 6 Flute Chucking Reamers and 6 Flute, 10° R.H. Spiral Chucking Reamers
Diameter: .213" and .272"
Axial Rake (AR): 0° and 10°
Radial Rake (RR): 0°
Helix Angle: 0° and 10°
Corner Angle: 45°
Peripheral Clearance: 10°

3.6 Reaming Conditions (continued)

Reaming Conditions

Feed: .005 to .015 inches/revolution
Depth of Hole: .500" through hole
Stock Removed: .010" on radius
Cutting Fluid: Highly Sulphurized Oil, Highly Chlorinated Oil and water soluble emulsions.
Tool Life End Point: .012" wear on reamer corner.

3.7 Tapping Conditions

Tapping tests were made with 5/16-24 NF high speed steel taps.

Machine

A Fosdick 25" Box Column Drilling Machine was used for the tapping tests.

Test Samples

The 1/2" thick slugs previously drilled and reamed were used for the tapping tests.

Tap Material

Type M-10 high speed steel plain and nitrided taps were used in the tests.

Tap Geometry

Tap: 4 Flute Plug, 2 Flute Chipdriver Plug
Percent Thread: 60% and 75%

Machining Conditions

Depth of Hole: .500" through hole
Cutting Fluid: Highly Sulphurized Oil and Highly Chlorinated Oil
Tool Life End Point: Galling and seizure of tap or tap breakage

3.8 Grinding Conditions

Grinding tests were made using various grinding wheels and a range of grinding conditions to effect the best Grinding Ratio.

Machine

The grinding tests were performed on a Norton 8" x 24" Hydraulic Surface Grinder equipped with a variable speed spindle drive to obtain wheel speeds from 1000 to 7500 feet per minute.

3.8 <u>Grinding Conditions</u> (continued)

Test Bars

The test bars had a nominal size of 1" thick x 1-1/2" wide x 6" long. All surfaces were clean-up machined prior to testing to remove any surface effects.

Grinding Wheels

The following grinding wheels were used for the tests:

Aluminum Oxide Wheels

32A46G8VBE
32A46H8VBE
32A46J8VBE
32A46K8VBE
32A46L8VBE
32A46N5VBE

Silicon Carbide Wheels

GC60J6VP
GC46K6VP
GC46L6VP
GC80N6VP

Grinding Conditions

Wheel Speed: 2000 to 6000 feet per minute
Down Feed: .0005 to .005 inches per pass
Cross Feed: .025 to .100 inches per pass
Table Speed: 20 to 60 feet per minute
Grinding Fluid: Highly Chlorinated Oil, Highly Sulphurized Oil, Water Soluble Emulsion and Chemical Solution

Test Procedure

The procedure used in the surface grinding tests to study the effectiveness of a set of grinding conditions was one of measuring the amount of wheel wear for a given amount of stock removed. See Figure 1. Wheel wear was measured using a vernier caliper and an accurate indicator and depth measurements were made to determine the stock removed. The volume of stock removed and volume of wheel removed was thus calculated.

3.8 Grinding Conditions (continued)

Test Procedure (continued)

The Grinding Ratio (G) which indicates the effectiveness of a set of grinding conditions is defined as:

$$G = \frac{\text{Volume of Stock Removed}}{\text{Volume of Wheel Removed}}$$

All test samples were examined for surface cracking, chatter marks and any other detrimental surface effects produced by the test grinding.

3.9 Distortion Studies and Residual Stress Analysis

Surface grinding tests were made on Pressed and Sintered Tungsten, 95% Density, 34 R_c to study the effect of grinding variables on distortion. Selected test specimens from the distortion studies were used for the residual stress analyses. The stress analyses were made to define the types and magnitude of residual stresses induced by the grinding operations.

Distortion Studies

The distortion studies were made using test specimens made under carefully controlled conditions. The test specimens were finish ground to size using a low stress grinding technique. The specimens were 3/4" wide by 4-1/4" long, see Figure 2. Thickness of the specimens was .070". The sample thickness after test grinding was .060" for each specimen.

The test specimens were held in a special fixture, Figure 3, for the grinding tests. The tapered clamp along the length of the sample provided positive clamping, which permitted uniform stock removal.

The curvature of each specimen was carefully measured before and after test grinding. Through this procedure the change in curvature, or workpiece distortion, resulting from the grinding process was established for a variety of grinding conditions. Figure 4 shows the fixture used in measuring curvature, and Figure 5 shows how the deflection measurements were obtained on this fixture.

Residual Stress Analysis

Residual stress analyses were made on selected test specimens from the distortion studies to determine the types and magnitude of the stresses induced by grinding.

3.9 Distortion Studies and Residual Stress Analysis (continued)

Residual Stress Analysis (continued)

The procedure used in the stress analysis was one of progressively etching off the test surface in uniform small increments and noting the change in deflection of the specimen. The deflection measurements were made using the same fixture used in the distortion studies, Figure 4. The depth of stock removed versus change in deflection data was then used to calculate the residual stress at any depth below the surface of the specimen. The calculations were made using the equation developed by Messrs. Thomsen and Frisch* and determine the uniaxial stress in the longitudinal direction of the test specimen.

Grinding Distortion Tests

Machine

The grinding tests were made on a Norton 8" x 24" Hydraulic Surface Grinder equipped with an infinitely variable speed drive on the spindle. Grinding wheel speeds ranging from 1000 to 7500 surface feet per minute can be obtained on this machine.

Grinding Wheels

The following wheels were used for the tests:

32A46H8VBE
32A46K8VBE
32A46N5VBE

Grinding Conditions

Wheel Speed: 2000 to 6000 feet per minute
Down Feed: .001 to .002 inches per pass

Low Stress Grinding Down Feed Progression:	.0005 inches per pass to last .002", .0004, .0004, .0002, .0002, .0002, .0002, .0002, .0002 inches per pass 1 sparkout pass

Stock Removed: .010"
Cross Feed: .050 inches per pass
Table Speed: 40 feet per minute
Grinding Fluid: Highly Sulphurized Oil, Highly Chlorinated Oil, Water Soluble Emulsions and KNO_2 Solution.

*Residual Grinding Stresses in Mild Steel - J. Frisch and E. G. Thomsen ASME Paper No. 50-F-10, 1950

4. TEST RESULTS

4.1 Unalloyed Tungsten, Forged and Resintered, 96% Theoretical Density, 35 R_c

4.1.1 Face Milling Tests

Face milling tests were made on forged and resintered tungsten at room temperature and with the workpiece heated to 800°F. The results of these tests are shown in Figures 6 and 7, pages 39 and 40.

The effect of cutting speed in face milling the forged and resintered tungsten at room temperature is shown in Figure 6, page 39. With a grade 883 (C-2) carbide cutter having a 15° negative axial rake and a 0° radial rake, the best tool life, 39" of work travel, was obtained at a cutting speed of 142 feet/minute using a feed of .009 inches/tooth with soluble oil cutting fluid. At cutting speeds below and above 142 feet/minute, tool life decreased rapidly. When the workpiece temperature was increased to 800°F, a tool life of less than 2" of work travel was obtained at a cutting speed of 75 feet/minute using a feed of .009 inches/tooth.

Figure 7, page 40, shows the effect of feed in face milling forged and resintered tungsten at room temperature. At a feed of .009 inches/tooth, the tool life was maximum, 39 inches of work travel; however, when the feed was reduced to .005 inches/tooth, tool life decreased to about 6 inches of work travel. At a feed of .014 inches/tooth, again only 6 inches of work travel was obtained and in addition the workpiece broke out as the cutter came out of the cut. Backing up the tungsten workpiece with cold rolled steel did not eliminate or even reduce this severe work breakout problem.

4.1.2 End Milling Tests

End milling tests were made using the cutter for slotting forged and resintered tungsten. The results of these tests are shown in Figure 8, page 41.

This chart shows the effect of cutting speed, carbide grade and workpiece temperature when using a 1-1/4" diameter carbide tipped end mill with a 0° axial rake and 0° radial rake. Best tool life, 26 inches of work travel, was obtained with a grade K-8 (C-3) carbide tipped cutter operating at a cutting speed of 204 feet/minute, a feed of .003 inches/tooth and a soluble oil cutting fluid. Tool life decreased to about 5 inches of work travel when the cutting speed was reduced to 100 feet/minute or increased to 300 feet/minute.

4.1.2 <u>End Milling Tests</u> (continued)

When a grade K-11 (C-4) carbide tipped end mill was used at 204 feet/minute, a tool life of 13 inches of work travel was obtained. Tool life decreased to 7 inches of work travel when a grade 44A (C-1) carbide tipped cutter was used at this cutting speed.

The effect of end mill slotting forged and resintered tungsten at a workpiece temperature of 800°F is also shown. This chart, Figure 8, page 41, shows that when the forged tungsten was heated to 800°F, less than 1 inch of work travel was obtained using a grade K-11 (C-4) carbide tipped cutter at 204 feet/minute with a feed of .003 inches/tooth. The chips came out red hot as soon as the cutter began to cut its full width and the test had to be discontinued.

Figure 9, page 42, shows the effect of cutting speed and carbide grade when taking peripheral end milling cuts on pressed and sintered tungsten, 93% density, 34 R_C. The width of cut was 1/4" and the depth 1/8". With a workpiece temperature of 800°F, the best tool life, 109 inches of work travel, was obtained at a cutting speed of 140 feet/minute using a feed of .004 inches/tooth and a grade K-8 (C-3) carbide tipped cutter. When the cutting speed was increased to 200 feet/minute, the tool life dropped to about 50 inches of work travel.

This chart also shows the effect of carbide grade in peripheral end milling this pressed and sintered tungsten. A grade K-6 (C-2) carbide tipped cutter gave 99 inches of work travel, while a grade K-11 (C-4) cutter gave 55 inches of work travel at a cutting speed of 140 feet/minute using a feed of .004 inches/tooth and a workpiece temperature of 800°F.

Figure 9, page 42, also shows the tool life obtained when peripheral end milling pressed and sintered tungsten at room temperature. At a cutting speed of 200 feet/minute and a feed of .004 inches/tooth, a tool life of 20 inches work travel was obtained. By comparison, a tool life of 50 inches work travel was obtained when the workpiece temperature was increased to 800°F.

4.1.3 <u>Drilling Tests</u>

The results of the drilling tests on tungsten are shown in Figures 10 through 13, pages 43 through 46.

4.1.3 Drilling Tests (continued)

In drilling 1/2" through holes in pressed and sintered, forged and resintered, and arc cast tungsten with .213" diameter grade 883 (C-2) solid carbide drills, Figure 10, page 43 shows the best drill life was 15 holes obtained in the forged and resintered tungsten at a cutting speed of 150 feet/minute and using a feed of .002 inches/revolution. With these drilling conditions, a drill life of 12 holes was obtained in the pressed and sintered material and 9 holes in the arc cast tungsten. Little or no work breakout was observed in the workpiece when the drill broke through.

Figure 11, page 44, shows the effect of cutting speed and feed in drilling pressed and sintered 45 R_c tungsten sheet 1/16" thick with 1/8" diameter grade 883 (C-2) solid carbide drills. Best drill life, 30 holes, was obtained at a cutting speed of 250 feet/minute with a feed of .0003 inches/revolution. When the feed was reduced to .0002 inches/revolution, drill life dropped to 12 holes and when the feed was increased to .0008 inches/revolution, drill life decreased to less than 5 holes. These tests were performed with a 90^o point angle drill with a notched drill web.

The effect of sheet thickness is shown in Figure 12, page 45. This chart shows that drill life is increased some six fold when 1/16" thick sheet is drilled compared to drilling 1/8" thick sheet tungsten, using 1/8" diameter solid carbide drills. At a cutting speed of 250 feet/minute with a feed of .0003 inches/revolution, 30 holes were drilled in 1/16" thick sheet while 5 holes were drilled in 1/8" thick sheet material with a 90^o point angle drill.

The effect of point angle is shown in Figure 13, page 46, in drilling pressed and sintered, 45 R_c, 1/16" thick sheet tungsten. At a cutting speed of 300 feet/minute and a feed of .0003 inches/revolution, a drill life of 19 holes was obtained with a 90^o point angle grade 883 (C-2) solid carbide 1/8" diameter drill, while 15 holes were drilled using a 90^o/135^o point angle, and a 118^o point angle drill provided 10 holes. All of these tests were performed using a highly chlorinated oil cutting fluid.

4.1.4 Tapping Tests

The results of the tapping tests on pressed and sintered tungsten, 95% density, 34 R_c, are presented in Figures 14 through 18, pages 47 through 51.

4.1.4 <u>Tapping Tests</u> (continued)

In tapping 1/2" through holes using 5/16-24 NF, 4 flute plug stub taps, Figure 14, page 47, shows the effect of workpiece temperature. A tap life of 14 holes was obtained when the workpiece was held at 400°F, 600°F and 800°F. When the workpiece temperature was decreased to 200°F, the tap life dropped to 8 holes, and with the workpiece at room temperature only 2 holes could be tapped.

Figure 15, page 48, shows the effect of cutting speed in tapping pressed and sintered tungsten at 600°F using 5/16-24 NF standard taps. Maximum tap life of 13 holes was obtained at a cutting speed of 5.3 feet/minute. When the cutting speed was increased to 15 feet/minute, tap life decreased to one hole.

The effect of workpiece temperature and tap design is shown in Figure 16, page 49. Fourteen holes could be tapped in the pressed and sintered tungsten when the workpiece temperature was increased to 800°F using a stub type tap. With a standard length tap, only 6 holes were tapped. Tests performed at room temperature showed that a nitrided standard length tap provided 5 holes, while a stub length tap and an untreated standard length tap provided 2 holes.

Figure 17, page 50, shows a photograph of the special stub tap used for these tests and a standard length four flute tap. The overall length of the stub tap is 2 inches compared to 2-3/4 inches overall length for the standard tap. The flute length of the stub is 1/2". The maximum depth through hole that can be tapped is 9/16". This stub design provides for maximum rigidity which is necessary in tapping tungsten.

The effect of percent thread is shown in Figure 18, page 51. This chart shows very little difference in tap life when a 60% and 75% thread is tapped. Three 60% holes were tapped in the pressed and sintered tungsten while two 75% holes were obtained using a 5/16-24 NF standard length tap operating at 5.3 feet/minute with a highly chlorinated oil.

4.1.5 <u>Distortion Studies and Residual Stress Analysis - Distortion in Surface Grinding Tests</u>

The results in workpiece distortion studies in surface grinding are shown in Figures 19 through 21, pages 52 through 54.

4.1.5 Distortion Studies and Residual Stress Analysis - Distortion in Surface Grinding Tests (continued)

Figure 19 shows the effect of wheel speed and grinding fluid on distortion in grinding pressed and sintered tungsten 95% density, 34 R_C. With a soluble oil grinding fluid, the distortion increased from less than .001" at wheel speeds of 2000 and 3000 feet/minute to almost .007" when the wheel speed was increased to 4000 feet/minute. With a nitrite solution, however, the distortion decreased from .004" at a wheel speed of 2000 feet/minute to .002" when the wheel speed was increased to 4000 feet/minute. These tests were performed with a 32A46N5VBE grinding wheel, a table speed of 40 feet/minute, a down feed of .001 inches/pass and a cross feed of .050 inches/pass.

The effect of wheel grade is shown in Figure 20, page 53. This chart shows that the distortion did not change appreciably when the wheel hardness was increased from a J grade to an N grade.

Figure 21, page 54, shows that down feed also has little effect on distortion in grinding pressed and sintered tungsten, 95% density, 34 R_C. With a 32A46N5VBE wheel operating at 2000 feet/minute using a nitrite grinding fluid, the distortion remained almost constant at .004" over a down feed range of .0005 inches/pass to .002 inches/pass.

Residual Stress Analysis Tests

Stress analyses were performed on selected specimens from the distortion studies to evaluate the magnitude and type of residual stresses produced by surface grinding pressed and sintered tungsten. The calculated stress at any depth is plotted to show the distribution of the residual stress below the ground surface. The area under the stress distribution curve is a measure of the total induced stress. The greater the area under the curve, the greater the total stress in the surface and, hence, the greater the distortion that is produced.

The results of the stress analysis on the surface ground specimens are given in Figures 22 through 26, pages 55 through 59.
The effect of wheel grade is shown in Figure 22, page 55. The stress distribution curves show that a relatively soft J grade wheel produced a greater stress than the harder L and N grade grinding wheels. A maximum stress of 70,000 to 90,000 psi was produced in the test specimens .0005 inches below the surface. This stress was compressive in nature. At depths beyond .002" below the surface, little or no stress was produced in test specimens.

4.1.5 Distortion Studies and Residual Stress Analysis - Residual Stress Analysis Tests (continued)

Figure 23, page 56, shows the effect of wheel speed when surface grinding with a 32A46N5VBE wheel using a nitrite grinding fluid. With a wheel speed of 2000 feet/minute, a maximum compressive stress of 90,000 psi was produced at a depth of .0005 inches below the surface. When the wheel speed was increased to 4000 feet/minute, the maximum compressive stress produced was about 70,000 psi at slightly more than .0005 inches below the surface. The residual stress distribution seen in this chart checks favorably with the distortion observed in the test specimens discussed previously.

The effect of wheel speed in surface grinding with a 32A46N5VBE wheel using a soluble oil grinding fluid is shown in Figure 24, page 57. The maximum stress was produced when a wheel speed of 4000 feet/minute was used. When the wheel speed was reduced to 2000 feet/minute, the residual stress was also reduced. It is interesting to note that the stress was tensile in nature when a soluble oil grinding fluid was used and compressive when a nitrite grinding fluid was used.

Figure 25, page 58, indicates that a down feed of .002 inches/pass produced a lower residual stress than down feeds of .001 and .0005 inches/pass. These tests were run using a 32A46N5VBE wheel operating at 2000 feet/minute with a nitrite grinding solution. The stresses are all compressive in nature, which is consistent with the data shown previously.

The effect of grinding fluid is shown in Figure 26, page 59, on the residual stress produced in pressed and sintered tungsten. This chart shows that approximately the same stress distribution is produced in the workpiece when a highly sulphurized grinding oil and a nitrite grinding solution is used. Both grinding fluids produce compressive stresses of about 90,000 psi in the specimen .0005" below the surface. When a soluble oil is used in grinding, the stress produced is tensile in nature and reaches a peak of about 30,000 psi right at the surface of the specimen.

4.2 D-31 Columbium, 217 BHN

4.2.1 Face Milling Tests

Face milling data for the D-31 Columbium, 217 BHN, is shown in Figures 27 and 28, pages 60 and 61.

The effect of cutting speed on tool life is shown in Figure 27, page 60, when using a 4 inch diameter single tooth face mill with grade K-6 (C-2) carbide. At a cutting speed of 142 feet/minute and a feed of .010 inches/tooth, a tool life of 94 inches work travel per tooth was obtained on this alloy. The tool life decreased to 22 inches work travel when the cutting speed was increased to 220 feet/minute, and 18 inches work travel when the cutting speed was increased to 330 feet/minute.

Figure 28, page 61, shows the effect of carbide grade in face milling this alloy. No difference in tool life was observed when grades 44A (C-1), 370 (C-6) and K-6 (C-2) were used. At a cutting speed of 357 feet/minute all three carbide grades provided a tool life of 6 inches work travel per tooth. This comparison of various grades of carbides was made at a relatively high cutting speed and a resulting short tool life so as to conserve the amount of columbium alloy used. This alloy is very expensive.

4.2.2 End Milling Tests

End milling test data is presented in Figures 29 through 31, pages 62 through 64 for this alloy.

Figure 29, page 62, shows the effect of cutting speed when end mill slotting D-31 Columbium with type M-2 and T-15 HSS cutters. When using a 1/2" diameter M-2 HSS cutter, a tool life of 126 inches work travel was obtained at a cutting speed of 54 feet/minute with a feed of .002 inches/tooth before the test was stopped with a wearland of only .006". This test was made using a soluble oil cutting fluid. When the cutting fluid was changed to highly chlorinated oil, a tool life of 176 inches work travel was obtained at a cutting speed of 70 feet/minute with a feed of .003 inches/tooth before the test was stopped with a wearland of .010 inches. With a type T-15 HSS cutter, a tool life of 192 inches work travel was obtained at a cutting speed of 102 feet/minute and a feed of .003 inches/tooth before the test was stopped with a wearland of .008 inches on the cutter.

4.2.2 End Milling Tests (continued)

The effect of feed is shown in Figure 30, page 63, when end mill slotting D-31 Columbium with 1/2" diameter 4 tooth, M-2 HSS cutters. Best tool life, 220 inches work travel, was obtained at a cutting speed of 102 feet/minute and a feed of .002 inches/tooth. Using this same cutting speed, a tool life of 130 inches work travel was obtained when the feed was reduced to .001 inches/tooth, and to less than 10 inches work travel when the feed was increased to .003 inches/tooth.

Figure 31, page 64, shows the effect of cutting fluid in end mill slotting the D-31 Columbium alloy. A highly chlorinated oil provided a tool life of 100 inches of work travel when cutting at 83 feet/minute with a feed of .003 inches/tooth. Tool life decreased to 62 inches of work travel when a highly sulphurized oil was used, 12 inches work travel with a soluble oil cutting fluid.

4.2.3 Drilling Tests

The test results obtained in drilling the D-31 Columbium alloy are presented in Figure 32, page 65. A drill life of 60 holes was obtained with a cutting speed of 100 feet/minute, a feed of .002 inches/revolution using a highly sulphurized oil, and a split point grind on the drill. With a chisel point grind, 45 holes were drilled at a cutting speed of 60 feet/minute with a highly sulphurized oil. When using a highly chlorinated oil with a feed of .002 inches/rev., a drill life of 32 holes was obtained at a cutting speed of 75 feet/minute. The cutting speed had to be reduced to 30 feet/minute to obtain a tool life of 35 holes when the feed was increased to .005 inches/rev. with a highly chlorinated cutting oil.

4.2.4 Reaming Tests

The test data obtained in reaming this D-31 Columbium alloy are presented in Figures 33 and 34, pages 66 and 67.

Figure 33, page 66, shows that a reamer life of 105 holes was obtained at a cutting speed of 125 feet/minute with a feed of .005 inches/revolution using a highly sulphurized cutting oil. Reamer life decreased to 55 holes when the cutting speed was increased to 150 feet/minute and dropped to 30 holes when a cutting speed of 175 feet/minute was used. This chart also shows the effect of cutting fluids in reaming this alloy. When using a soluble oil, a reamer life of 15 holes was obtained compared with 105 holes with the highly sulphurized oil. A highly chlorinated oil provided only 10 holes at a cutting speed of 150 feet/minute compared with 55 holes with the highly sulphurized oil.

4.2.5 Tapping Tests

The effect of cutting fluid in tapping this alloy is shown in Figure 35, page 68. This chart shows that the most effective cutting fluid was a highly chlorinated oil. Highly sulphurized oils, inhibited trichloroethane additives and soluble oil did not perform nearly as well as the straight chlorinated oil.

A tap life of 50 holes was obtained when tapping the D-31 Columbium alloy at a cutting speed of 12 feet/minute using a 1/4-28 NF, 2 flute plug tap with a highly chlorinated cutting oil. This data presented in Figure 36, page 69, also shows that tap life decreases rapidly when cutting speed is increased. At a cutting speed of 17 feet/minute, a tap life of 17 holes was obtained and at a cutting speed of 25 feet/minute, less than 5 holes could be tapped.

4.3 Silica Fiber Reinforced Phenolic Resin

4.3.1 Turning Tests

The effect of cutting speed and tool material in turning Silica fiber reinforced phenolic resin is shown in Figure 37, page 70. Maximum tool life, 15 minutes, was obtained at a cutting speed of 100 feet/min. with a feed of .009 inches/rev. using a grade K-6 (C-2) carbide. Tool life decreased to 8 minutes when the speed was increased to 200 feet/minute and 6 minutes when a cutting speed of 300 feet/minute was used. A grade K-7H (C-8) carbide provided 3 minutes of tool life, and a grade 370 (C-6) carbide provided one minute tool life at 200 feet/minute.

Figure 38, page 71, shows the effect of feed in turning this material. The optimum feed in turning this material appears to be .015 inches/rev. With this feed and a cutting speed of 200 feet/minute, a tool life of 25 minutes was obtained. When the feed was reduced to .005 inches/rev. or increased to .022 inches/rev., tool life decreased rapidly.

4.3.2 Face Milling Tests

It is possible to face mill Silica fiber reinforced phenolic resin at very high cutting speeds. The face milling data shown in Figure 39, page 72, was obtained at a cutting speed of 1300 feet/minute. With this cutting speed, maximum tool life of 175 inches of work travel per tooth was obtained with a grade K-6 (C-2) carbide tipped cutter. A tool life of 105 inches work travel per tooth was obtained when the feed was reduced to .004 inches/tooth while tool life decreased to 140 inches work travel per tooth when a feed of .015 inches/tooth was used.

4.3.3 Drilling Tests

Very high drilling speeds are also possible when using solid carbide drills in drilling this material. The test data in Figure 40, page 73, shows that a drill life of almost 400 holes was obtained when drilling Silica fiber reinforced phenolic resin at a cutting speed of 300 feet/min. with a feed of .015 inches/rev. using a grade 883 (C-2) solid carbide twist drill. Drill life decreased to 200 holes when the feed was reduced to .009 inches/rev. and 75 holes when a feed of .005 inches/rev. was used.

Figure 41, page 74, shows the test data obtained when drilling Silica fiber reinforced phenolic resin with high speed drills. Best drill life, 14 holes, was obtained at a cutting speed of 25 feet/minute with a feed of .015 inches/rev. using a type M-1 HSS drill. Drill life decreased to 9 holes at a cutting speed of 50 feet/minute and 3 holes when the cutting speed was increased to 100 feet/minute.

4.3.4 Tapping Tests

The test data obtained in tapping silica fiber reinforced phenolic resin is presented in Figures 42 and 43, pages 75 and 76.

Best tap life, 45 holes, was obtained at a tapping speed of 25 feet/min. See Figure 42, page 75. When the cutting speed was increased to 30 feet/minute, tap life decreased to 30 holes, and at a cutting speed of 41 feet/minute 19 holes were tapped. This material is very abrasive and the lead threads wear quite rapidly. If the tap is not taken out of service when the lead threads become worn, even though the back threads look perfectly good, the resulting threads in the workpiece will be torn and ragged.

Figure 43, page 76, shows the effect of tap design in tapping Silica fiber reinforced phenolic resin. A four flute plug style tap appears to perform somewhat better than a two flute chip driver plug style tap. At a cutting speed of 25 feet/minute, the four flute plug tap provided 45 holes while 35 holes were obtained using a 2 flute chip driver tap at this same cutting speed.

4.3.5 Surface Grinding Tests

Surface grinding this material presented no problem with respect to grindability. With a silicon carbide grinding wheel operating at 6000 feet/minute, 5 cubic inches of material was removed from the workpiece with no measurable wheel wear.

4.3.5 Surface Grinding Tests (continued)

The one problem encountered was the dust generated in the grinding process since this material must be ground dry. The dust problem was solved by attaching an industrial type vacuum cleaner hose, with a funnel shaped nozzle, to the spindle head and collecting most of the dust as it was generated by the grinding wheel.

Silicon carbide grinding wheels perform best in grinding this material. It is possible to use wheel speeds of 5000-6000 feet/minute without burning the workpiece. Similarly, down feeds of .010-.025 inches/pass were made without any serious workpiece damage. Table speeds and cross feeds can be varied within wide limits consistent with the type of finish required.

4.4 Solid Zirconium Oxide, 70% and 99% Density

4.4.1 Surface Grinding Tests

The results of the surface grinding tests on solid zirconium oxide are presented in Figures 44 through 47, pages 77 through 80.

Figure 44 shows the Grinding Ratio obtained when the wheel speed is varied from 2000 feet/minute to 5000 feet/minute for this material in two theoretical densities, 70% and 99%. The 70% dense material could be ground considerably better than the 99% dense material. With a GC60J6VP silicon carbide grinding wheel operating at a speed of 2000 feet/minute, a G Ratio of 84 was obtained on the 70% dense material while a G Ratio of only 9 was obtained on the 99% dense material. These tests were performed with a nitrite solution to hold down the dust. When grinding dry, the Grinding Ratio decreased to about 70 when grinding the 70% dense zirconium oxide. The Grinding Ratio was about 5 when grinding the 99% dense material dry using the above mentioned grinding conditions.

Note that the wheel speed has considerably more effect on the Grinding Ratio when grinding the 70% dense material compared to grinding the 99% dense zirconium oxide. The Grinding Ratio decreased from 80 to 28 when the wheel speed was increased from 2000 feet/minute to 5000 feet/minute in grinding the 70% dense zirconium oxide. However, the G Ratio remained essentially constant at about 10 when the wheel speed was increased from 2000 feet/minute to 5000 feet/minute in grinding the 99% dense material.

The effect of down feed in grinding solid zirconium oxide is shown in Figure 45, page 78. A G Ratio of 10 to 12 was obtained over a down feed range of .002 to .004 inches/pass when grinding the 99% dense

4.4.1 Surface Grinding Tests (continued)

material. The G Ratio decreased to about 7 when the down feed was increased to .005 inches/pass. The effect of down feed is much more pronounced in grinding the 70% dense zirconium oxide. The Grinding Ratio increased from 27 to 53 when the down feed was increased from .002 to .004 inches/pass. But when the down feed was increased to .005 inches/pass, the G Ratio decreased from 53 to 35.

The effect of table speed is shown in Figure 46, page 79, in surface grinding solid zirconium oxide. No change in G Ratio was observed when the table speed was increased from 20 feet/minute to 60 feet/min. in grinding the 99% dense material. However, the G Ratio increased from 27 to 82 when the table speed was increased from 20 feet/minute to 60 feet/minute in grinding the 70% dense material.

Figure 47, page 80, shows the effect of cross feed in surface grinding this material. Again, no appreciable change in G Ratio was observed when the cross feed was increased from .025 inches/pass to .100 in./pass in grinding the 99% dense zirconium oxide. The G Ratio increased from about 30 to 90 over the same cross feed increase when grinding the 70% theoretical density material.

4.5 Flame Sprayed Zirconium Oxide and Aluminum Oxide Coatings

4.5.1 Surface Grinding Tests

Figure 48, page 81, shows the Grinding Ratios obtained when surface grinding flame sprayed zirconium oxide and aluminum oxide coatings. A G Ratio of 80 was obtained when grinding the zirconium oxide coating and a G Ratio of 19 was obtained from the aluminum oxide coating. These tests were performed using a 39C60J8VK silicon carbide wheel operating at 5000 feet/minute using a down feed of .002 inches/pass and a table speed of 20 feet/minute. A nitrite solution was used to hold down the dust.

The effect of wheel grade in grinding the flame sprayed aluminum oxide coating is shown in Figure 49, page 82. This chart shows that a relatively soft "J" grade silicon carbide wheel performed better than a harder "N" grade wheel. With a wheel speed of 5000 feet/min. and a down feed of .002 inches/pass, a G Ratio of 19 was obtained with the "J" grade and a G Ratio of 9 with the "N" grade wheel.

A two-fold increase in G Ratio was obtained in surface grinding the flame sprayed aluminum oxide when using a nitrite solution compared to dry grinding. With a 39C60J8VK silicon carbide wheel operating at 5000 feet/minute, a G Ratio of 19 was obtained when using a nitrite solution, and a G Ratio of 9 was obtained when grinding dry.

4.6 90Ta-10W Alloy

4.6.1 Turning Tests

The curves shown in Figure 50, page 83, present the relative merits of a wide variety of tool materials in turning the 90Ta-10W alloy. Note that the cutting speeds with the carbide tool C-2 grade K-6 are 60% to 80% higher than those permitted with the M-2 or T-15 high speed steel tools and 25% higher than with the cast alloy tools. Of the three grades of carbide tools tested, C-2, C-3 and C-6, the tool life with the C-2 grade was over 100% longer than with the C-6 and 30% longer than with the C-3 grade.

Comparative turning tests with three types of cutting fluids, soluble oil (1:20), highly chlorinated and highly sulphurized oils, indicated that soluble oil was considerably better than either of the straight oils.

The effect of feed is shown in Figure 51, page 84. The results indicate that the feed should be in the range of .006 to .010 inches/rev. Tool life decreased rapidly at feeds greater than .010 inches/rev. At light feeds, under .006 inches/rev., not only is the tool life in terms of cubic inches of metal removed low but the production rate is also low.

4.6.2 Face Milling Tests

Various tool materials were used in face milling the 90Ta-10W alloy. High speed steel appeared to be more practical for milling this alloy than carbide, see Figures 52 and 53, pages 85 and 86. Tool life was very short with the carbide tools because of the rapid nose breakdown at the cutting speeds used. A tool life of 40 inches of work travel was obtained with a single tooth Braecut high speed steel cutter at a feed of .006 inches/tooth and a cutting speed of 80 feet/min. By increasing the feed to .010 inches/tooth, the cutting speed can be increased to 100 feet/minute and still obtain the same tool life, see Figure 53, page 85. Neither the T-1 HSS nor the Stellite 98 M-2 cast alloy tool performed satisfactorily as a cutter in face milling the 90Ta-10W alloy. The tool life with the T-15 HSS cutter was almost double that obtained with the T-1 HSS tool, however it was about 20% less than that with the Braecut tool.

The feed is somewhat critical in face milling the tantalum alloy. The maximum tool life was obtained at a feed of .010 inches/tooth using the Braecut HSS cutter. Cutter life is reduced almost 50% if the feed is increased to .014 inches/tooth or decreased to .006 inches/tooth.

4.6.2 Face Milling Tests (continued)

Also, unless the proper tool geometry is used on the Braecut cutter, tool life is very short. See Figure 54, page 87. For example, milling cutters with an axial rake angle of 0^{o} and a radial rake angle of either 10^{o} negative or 0^{o} had a tool life of less than 5 inches of work travel; while under the same milling conditions a cutter with an axial rake of 0^{o} and a radial rake of 20^{o} had a tool life of 56 inches of work travel. The cutter life was short over a wide range of tool geometries with carbide cutters.

In face milling the 90Ta-10W alloy with Braecut HSS cutters using a soluble oil (1:20) cutting fluid resulted in a 35% improvement in tool life, over either the highly chlorinated or sulphurized oils.

4.6.3 End Mill Slotting Tests

As shown in Figure 55, page 88, end milling slotting can be performed at 25% higher cutting speeds with T-15 HSS cutters than with M-3 HSS cutters. The feed is very critical in this operation. Doubling the feed from .002 to .004 inches/tooth results in decreasing tool life from 48 to 28 inches work travel, see Figure 56, page 89. Another important factor in end milling the 90Ta-10W alloy is the cutting fluid. Cutter life was twice as great with a 1:20 soluble oil as it was with either a highly sulphurized or chlorinated oil.

4.6.4 Drilling Tests

Data for drilling 1/16" dia. holes in tantalum alloy sheet is shown in Figure 57, page 90. Note that in the 1/16" thick sheet, a feed of .002 inches/rev. is recommended, while in the thicker 1/8" sheet the feed is reduced to .001 inches/rev. It should also be pointed out that particularly with the feed of .002 inches/rev., the cutting speed is critical; a 10% increase in speed will result in a 50% reduction in drill life. In drilling small diameter holes, the drill length should be kept at a minimum. An indication of this is shown in the chart by the fact that at a cutting speed of 40 feet/minute, the drill life was 16 holes with a drill having a flute length of 1/4" and only 8 holes with a flute length of 7/8".

Both the cutting speed and feed rate are also critical with the larger diameter (.193") drills. The drill life curves shown in Figure 58, page 91, indicated a 20% increase in cutting speed (50 to 60 feet/min.) will result in decreasing the drill life from 44 holes to 7 holes at a feed of .002 inches/rev. Also, the production rate, as shown in Figure 58, page 91, remains unchanged even if the feed is increased to .005 inches/rev. since the cutting speed has to be decreased a proportional amount.

4.6.5 Reaming Tests

Figure 59, page 92, shows the relationship between cutting speed and reamer life. The effect of feed is also indicated in this chart. Note how rapidly reamer life drops if the cutting speed is increased beyond the optimum speed of 85 feet/minute. A 15% increase will result in reducing reamer life 75%. At a feed of .009 inches/rev. and a cutting speed of 75 feet/minute, reamer life was 64 holes. At this same cutting speed, the reamer life dropped more than 50% to 30 holes at a feed of .005 inches/rev. and to only 5 holes at a feed of .015 inches/rev. Also, unless a highly chlorinated oil is used, the reamer life is apt to be very short. Less than 10 holes could be reamed at the optimum feed when either a soluble or a highly sulphurized oil was used.

4.6.6 Tapping Tests

The effect of cutting speed and cutting fluid is shown in Figure 60, page 93, for tapping the 90Ta-10W alloy. Low cutting speeds, 5 feet/minute, and a highly chlorinated oil mixed 2 to 1 with inhibited trichloroethane are required for good tap life. The use of either a highly sulphurized oil or a soluble oil results in very poor tap life.

As shown in Figure 61, page 94, a two flute chip driver tap must be used. This tap style will tap about 40 holes while not even one hole can be tapped with a 4 flute plug tap under the same conditions.

4.6.7 Grinding Tests

The effect of wheel speed on G Ratio in grinding is presented in Figure 62, page 95, for two different grinding fluids. Note the improvement in G Ratio when a wheel speed of 2000 feet/minute is used with the 5% KNO_2 solution over the higher grinding speed or with the highly chlorinated oil.

Figure 63, page 96, shows that a further improvement in G Ratio is obtained if a harder wheel is used. Both the 32A46L5VBE and 32A80L6VBE wheels produced a G Ratio of 4, while the G Ratio with the 32A46J8VBE wheel was 3.

As shown in Figure 64, page 97, light down feeds produce the best G Ratios if a wheel speed of 2000 feet/minute is used with the KNO_2, 5% solution. Low table speeds, 20 feet/minute and cross feed of .025 inches/pass should be used. The G Ratio is about 50% higher with a 5% solution of KNO_2 than with either a soluble oil or a highly chlorinated oil, and 25% better than a highly sulphurized oil.

4.6.8 Recommendations for Machining 90Ta-10W Alloy

The machining data for the 90Ta-10W alloy has been reviewed, and general recommendations for machining are given in Table 1, pages 98 & 99.

4.7 Power Requirements and Coefficient of Friction in Machining

4.7.1 Thrust and Torque Measurements in Drilling

The torque required in drilling was measured using a drill dynamometer. This torque dynamometer is equipped with a linear differential transducer, the output of which was fed to a Sanborn Amplifier which recorded the torque values on chart paper. The thrust force was measured using a loop dynamometer.

The values of torque and thrust that were obtained in drilling the pressed and sintered, forged and resintered and arc cast tungsten are presented in Figures 65 through 67, pages 100 through 102. for several drill sizes. Note that the drill torque and thrust values were practically the same for each type of tungsten.

Figures 68 through 70, pages 103 through 105, show the drill torque and thrust values obtained in drilling D-31 Columbium, 90Ta-10W alloy and TZM Molybdenum alloy with high speed steel drills. These figures show that the thrust force can be reduced approximately 25% by grinding a split point on the drill. Torque and thrust also increase somewhat uniformly with an increase in drill diameter and feed.

The unit power requirements, P_D, in drilling can be calculated from the following equation:

$$P_D = \frac{T}{50,000\ d^2\ f}$$

where P_D = Unit Power requirements in drilling, hp./cu. in./min.

T = Torque measured with drill dynamometer, inch-pounds

d = diameter of drill, inches

f = feed, inches/rev.

4.7.1 <u>Thrust and Torque Measurements in Drilling</u> (continued)

Table 2 shows the average unit power required when drilling the refractory alloys tested in this program. The average unit power required when drilling pressed and sintered, forged and resintered and arc cast tungsten was about 2.25 hp/cu.in./min. This is approximately 125% higher than values that would be obtained in drilling a 38 R_c quenched and tempered steel. The unit power required in drilling D-31 Columbium, 90Ta-10W alloy and TZM Molybdenum alloy was about 1.25 hp/cu.in./min. This is about 50% lower than the values obtained for tungsten. The average unit power required in drilling D6AC steel quenched and tempered to 56 R_c is 2.10 hp/cu.in./min. as listed in Table 2, page 106.

4.7.2 <u>Force and Power Determination in Turning</u>

The forces acting on the cutting tool during the turning operation were measured using a mechanical type dynamometer. The dynamometer measures two force components; the cutting force (F_c) which acts in a direction tangent to the revolving work, and the thrust force (F_t) which acts in a direction parallel to the axis of the rotating workpiece.

Unit power (P_T) is used to compare the power required for different work materials. P_T is defined as the horsepower per unit volume of metal removed, and is expressed as the hp/cu.in./min. Unit power in turning was calculated from the following equation:

$$P_T = \frac{F_c}{396,000\ fd}$$

where F_c = cutting force measured by the tool dynamometer, pounds

f = feed, inches/rev.

d = depth of cut, inches

The coefficient of friction, μ, can be calculated from the equation:

$$\mu = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha}\ *$$

where F_c = Cutting force

F_t = Thrust force

α = Resultant rake angle

*Equation developed by Dr. M.E. Merchant, Cincinnati Milling Machine Company.

4.7.2 Force and Power Determination in Turning (continued)

Table 3 shows the average unit power and coefficient of friction when turning the materials tested in this program, pages 107 and 108.

This table also shows that the unit power averaged about 2.5 hp/cu.in./min. for the pressed and sintered, and arc cast tungsten and the 90Ta-10W alloy. The TZM Molybdenum and D-31 Columbium alloys had an average unit power of about 1.6 hp/cu.in./min.

5. PROGRAM FOR THE NEXT QUARTER

Machinability by Evaluation

The machinability research program for the next quarter will consist of completing the machining by conventional means of pressed and sintered, forged, and arc cast 93% to 100% theoretical density tungsten. Also, machining studies will be started on the B-120VCA titanium alloy.

The electrical characteristics of the Tornetic drilling and tapping units will be investigated. The relationship between rpm, feed, torque and dial setting will be determined. Means will be provided for recording these various factors simultaneously during the drilling or tapping operation. Preliminary tests will also be started using the Tornetic units.

The high speed spindle setup to be used on the Gray planer will be built. The variable speed drive for obtaining the required table speeds will be selected and installed.

The various machining operations will be started on the B-120VCA titanium. These operations include the following:

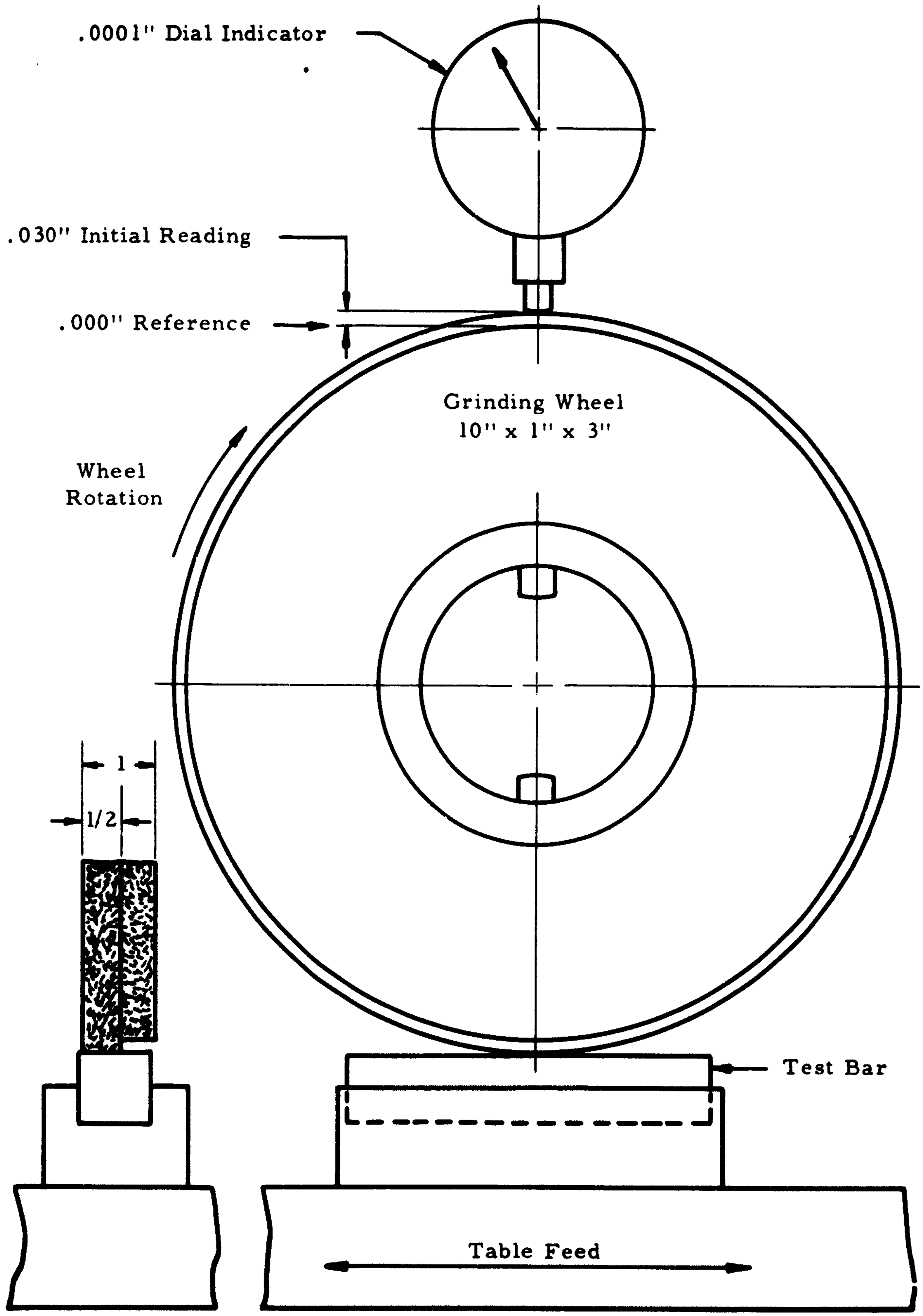
a. Turning with high speed steel and carbide tools.
b. Face milling with high speed steel and carbide tipped cutters.
c. End milling with high speed steel and carbide tipped cutters.
d. Drilling with high speed steel drills.
e. Tapping with high speed steel taps.
f. Grinding with various types of wheels and grinding fluids.

In each of the machining operations, the following variables will be investigated:

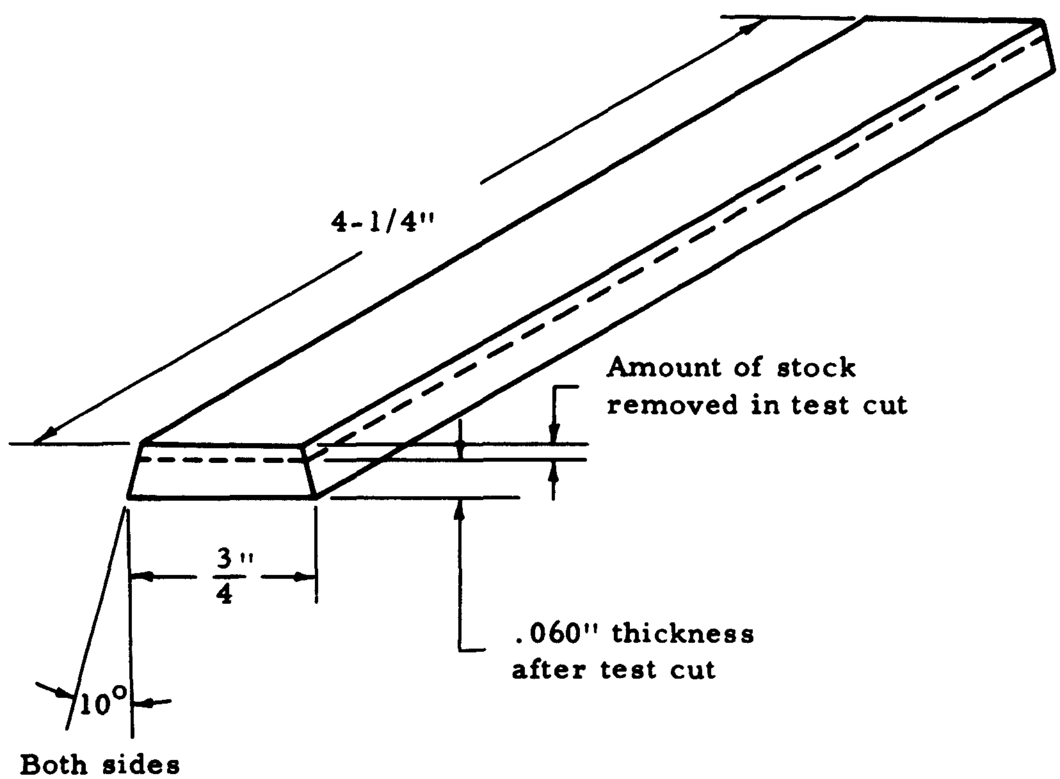
a. Cutting speed
b. Feed
c. Tool material
d. Tool geometry
e. Cutting fluid

The following variables will be investigated in the grinding tests:

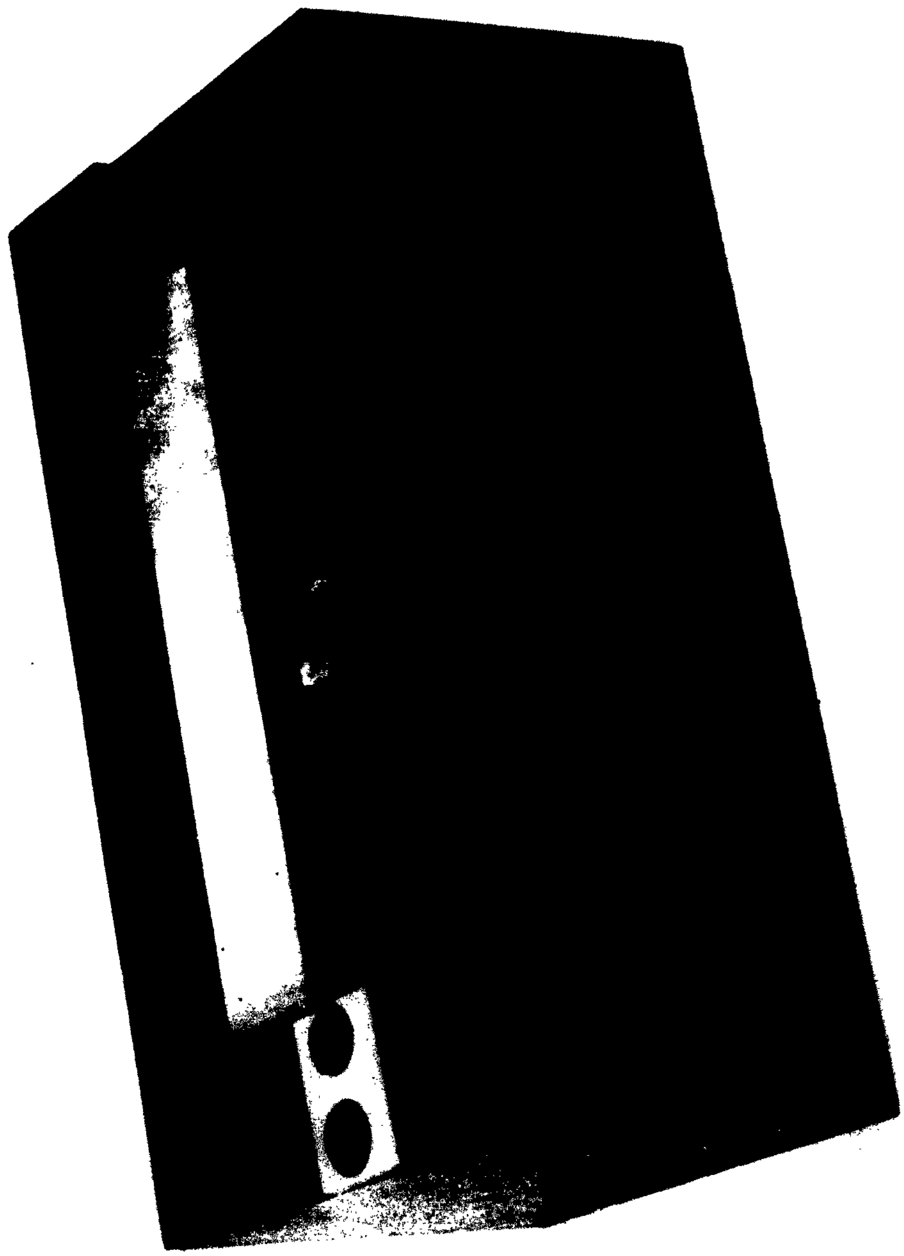
a. Wheel grade
b. Wheel speed
c. Down feed
d. Cross feed
e. Table speed
f. Grinding fluid



GRINDING TEST SETUP



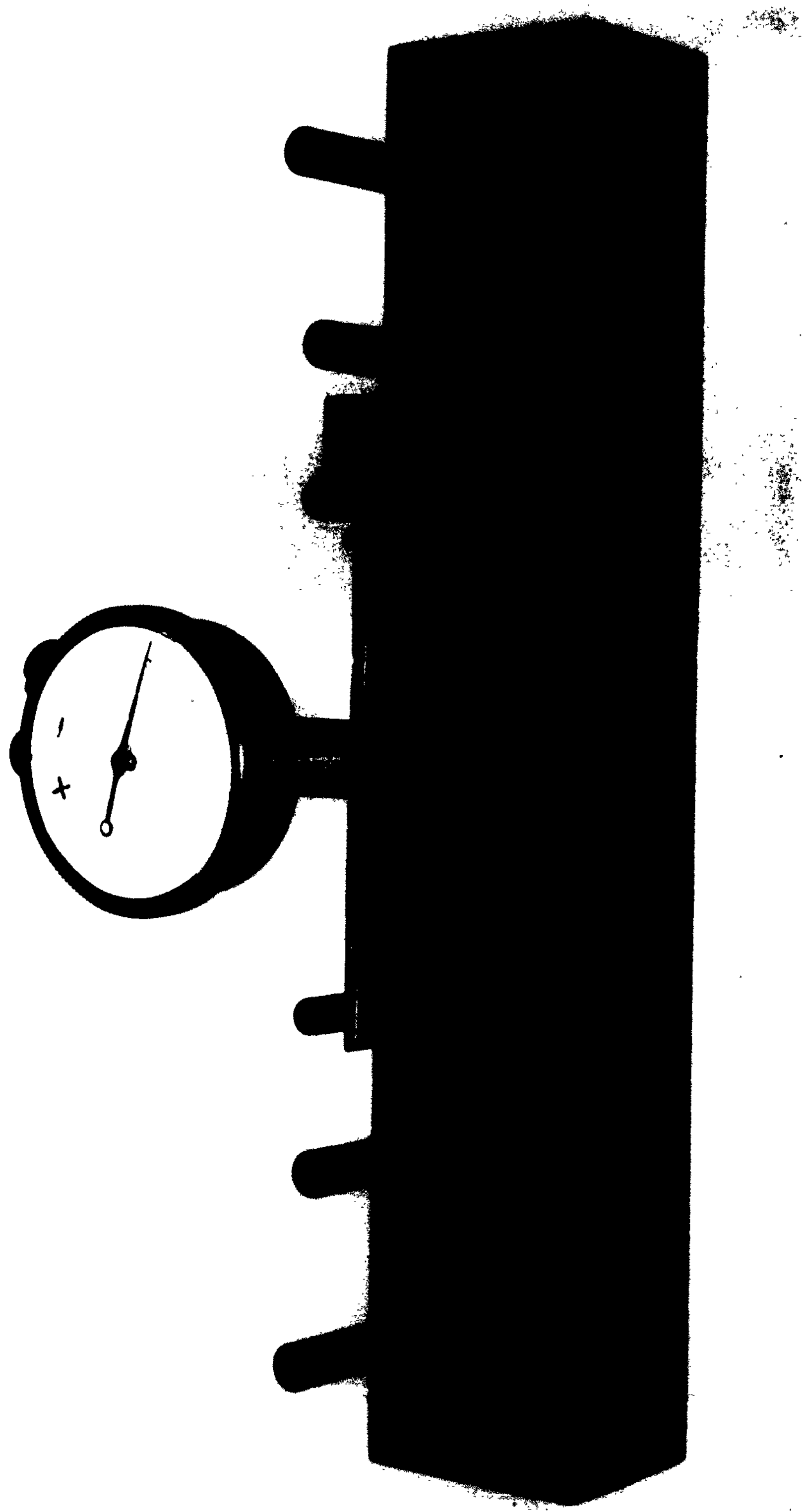
DISTORTION AND RESIDUAL STRESS TEST SPECIMEN



Distortion Specimen Holding Fixture

Figure 3

See text, page 13

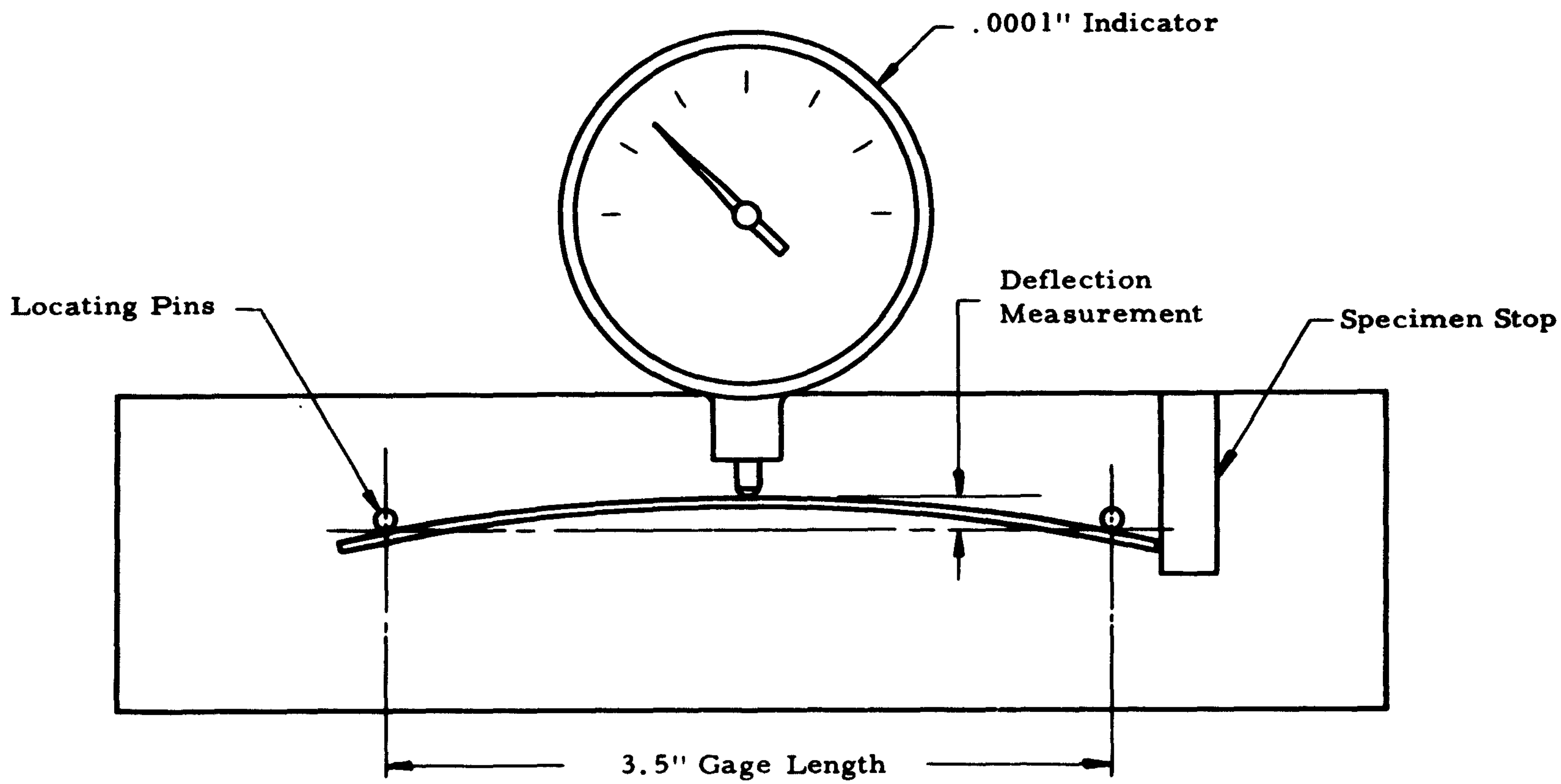


Fixture for Measuring Deflection of Distortion Test Specimen

See text, page 13

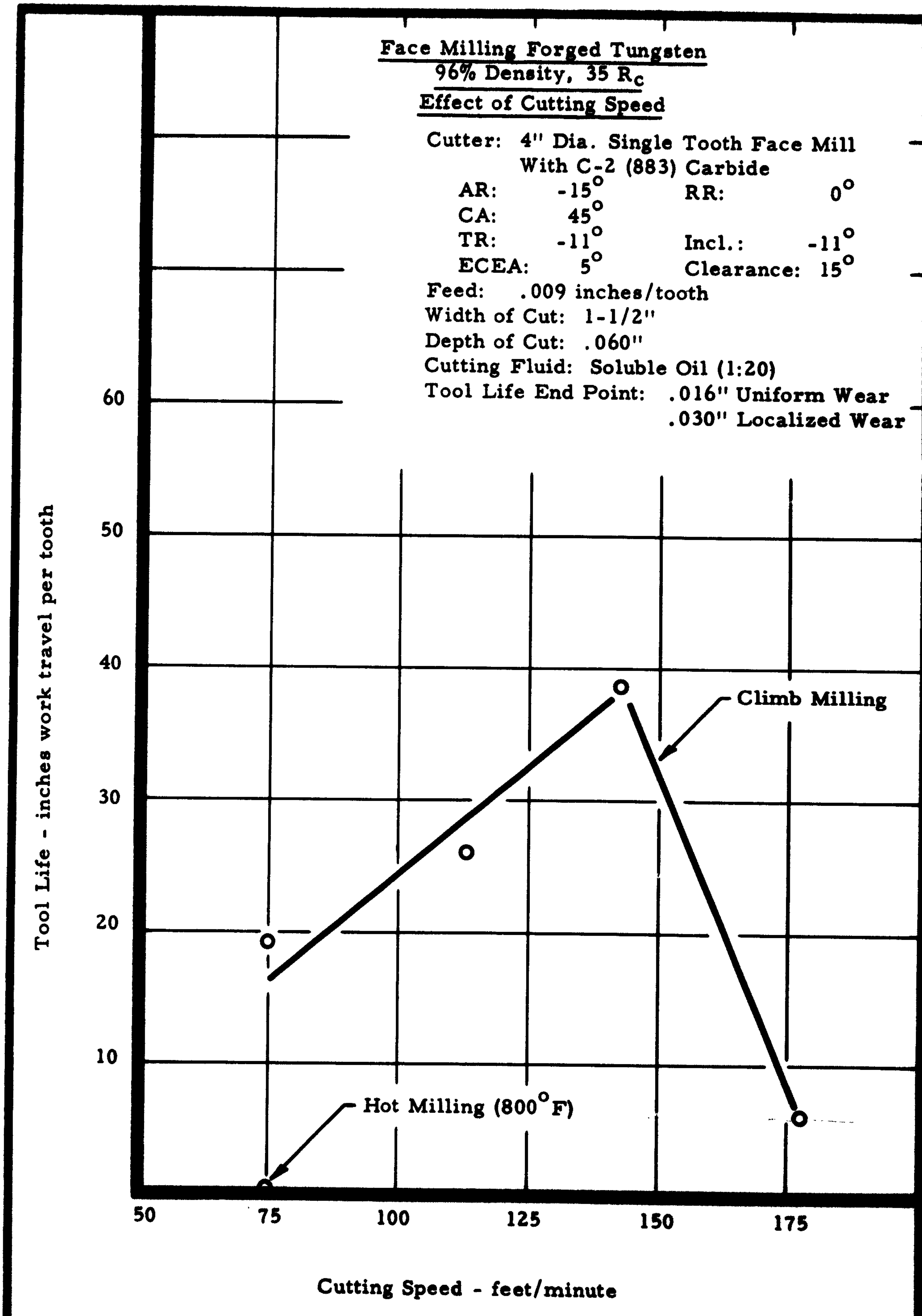
Figure 4

DEFLECTION MEASUREMENT FIXTURE



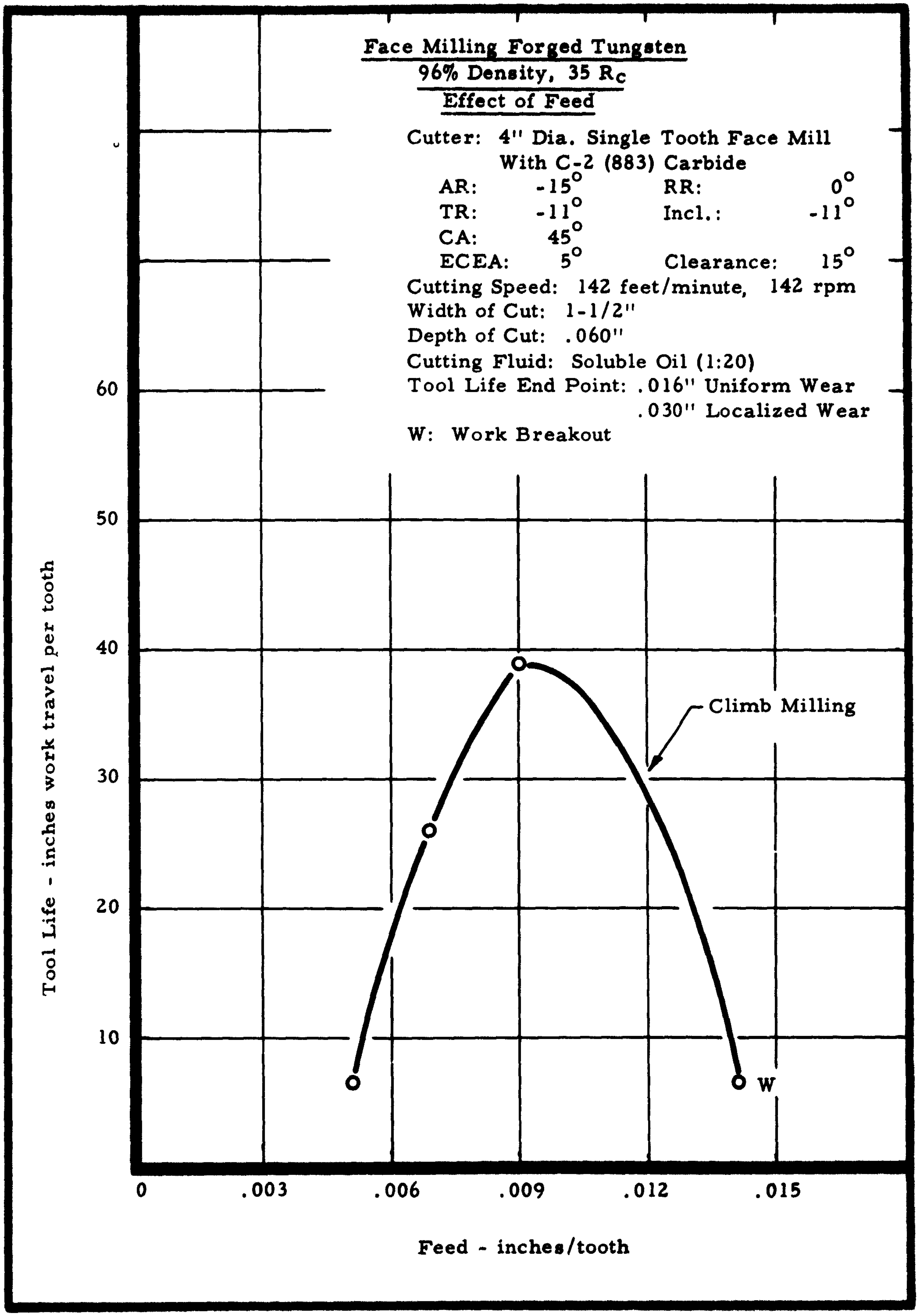
The above fixture is used to measure deflection of the test specimen in both the distortion and the residual stress analyses

See text, page 13

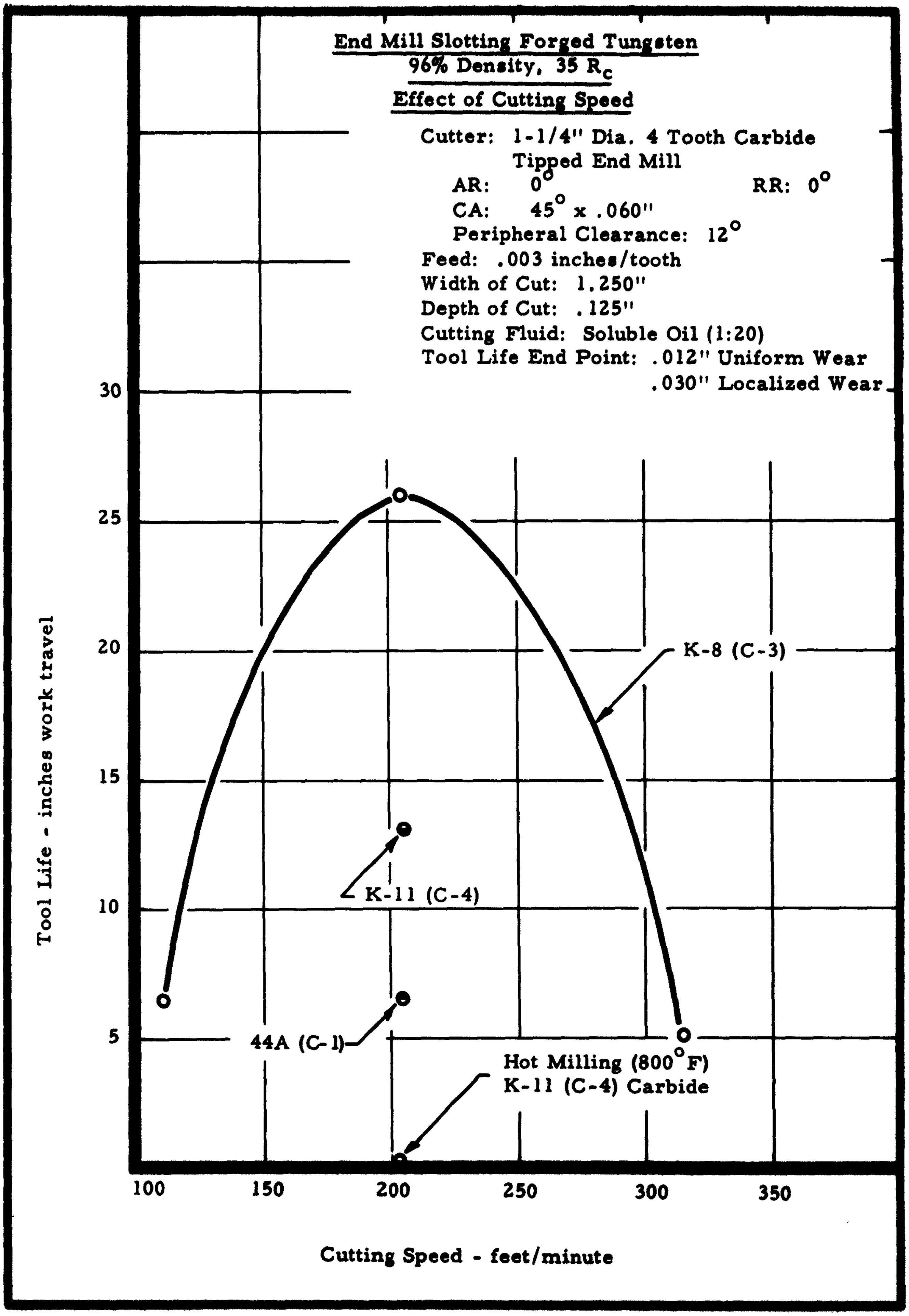


See Text page 15

Figure 6

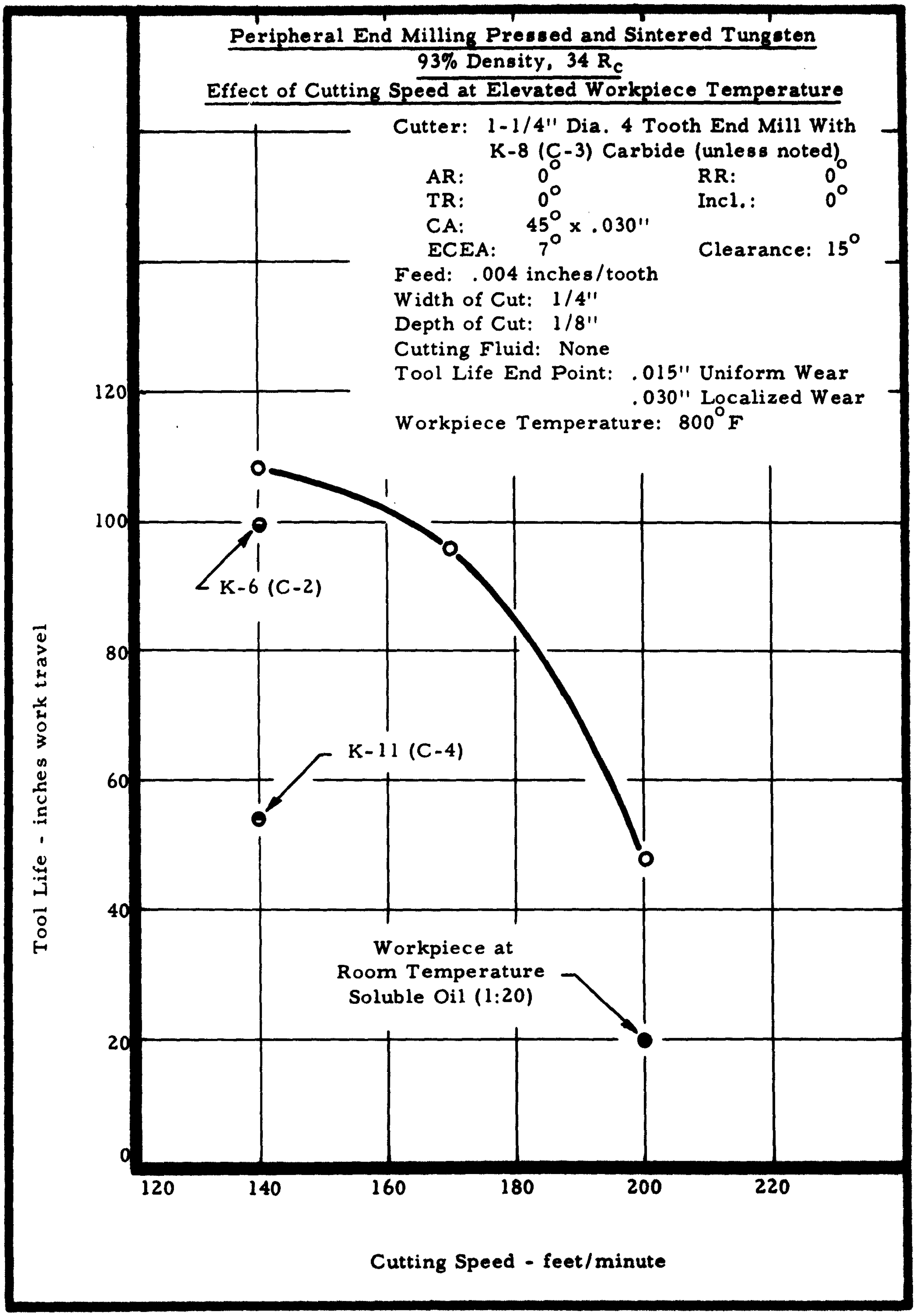


Face Milling Forged Tungsten
96% Density, 35 R_C
Effect of Feed
Cutter: 4" Dia. Single Tooth Face Mill
With C-2 (883) Carbide
AR: -15^{o}
RR: 0^{o}
TR: -11^{o}
Incl.: -11^{o}
CA: 45^{o}
ECEA: 5^{o}
Clearance: 15^{o}
Cutting Speed: 142 feet/minute, 142 rpm
Width of Cut: 1-1/2"
Depth of Cut: .060"
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .016" Uniform Wear
.030" Localized Wear
W: Work Breakout
Climb Milling
W
Tool Life - inches work travel per tooth
60
50
40
30
20
10
0
.003
.006
.009
.012
.015
Feed - inches/tooth



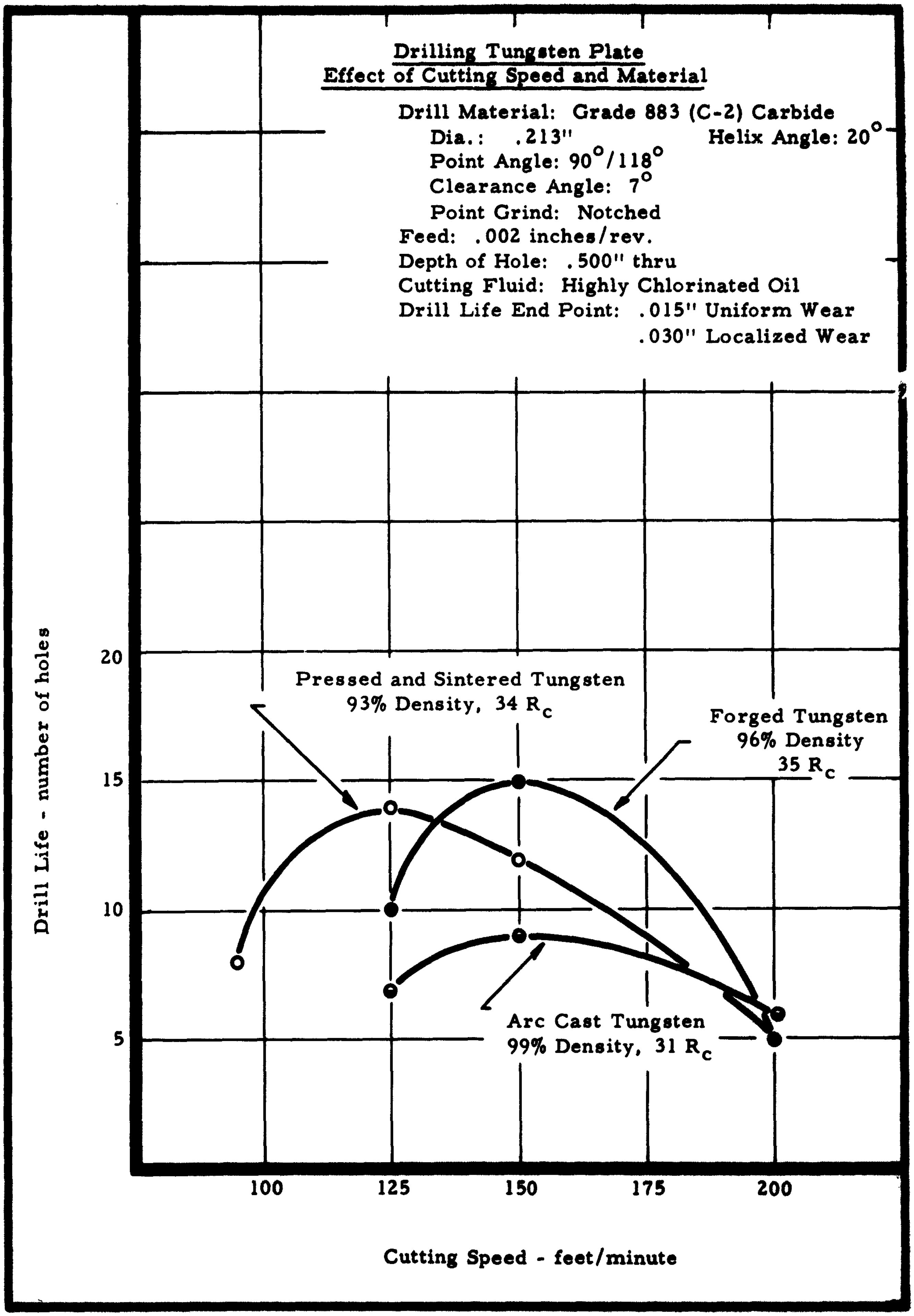
See Text page 15

Figure 8

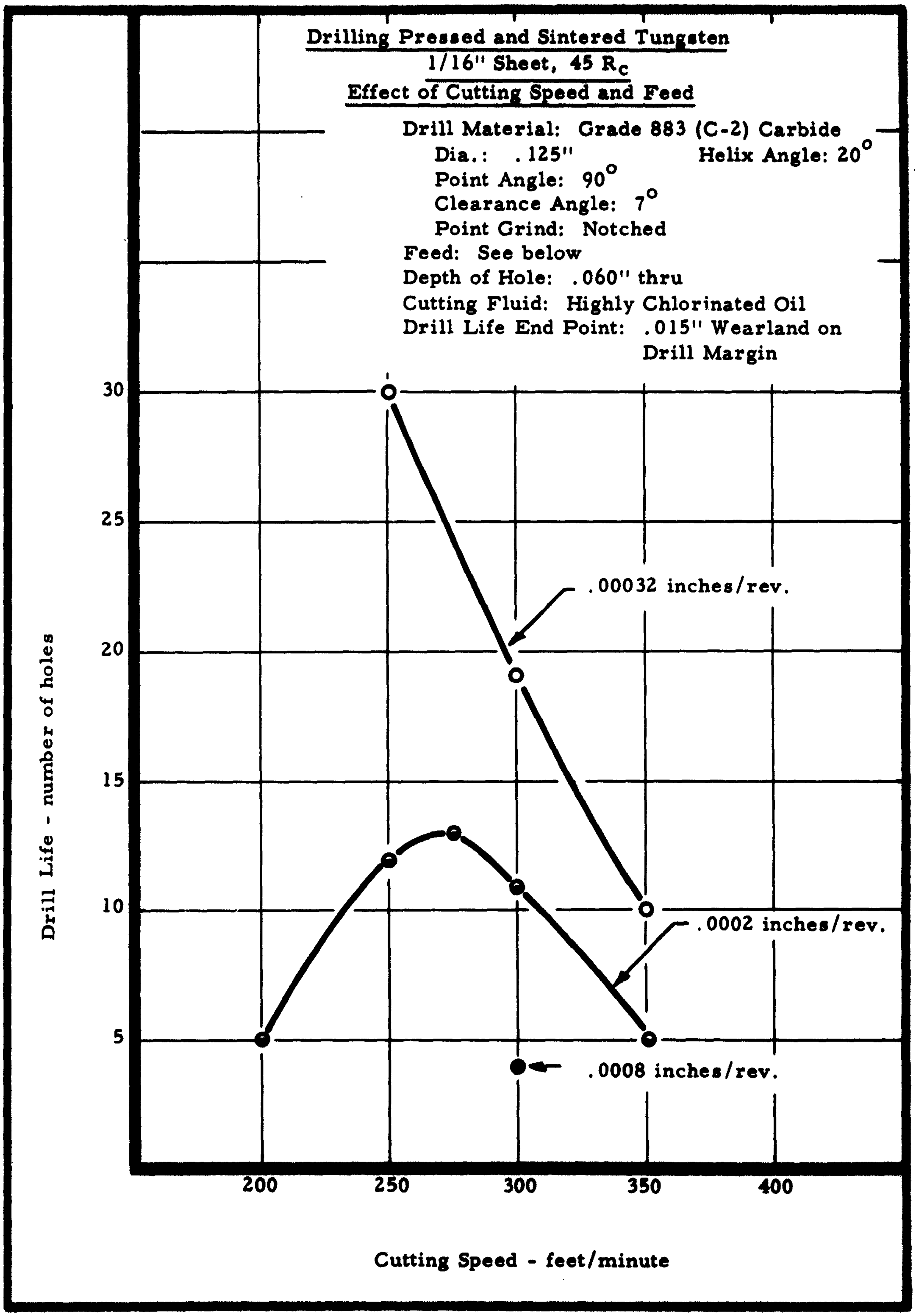


See Text page 15

Figure 9

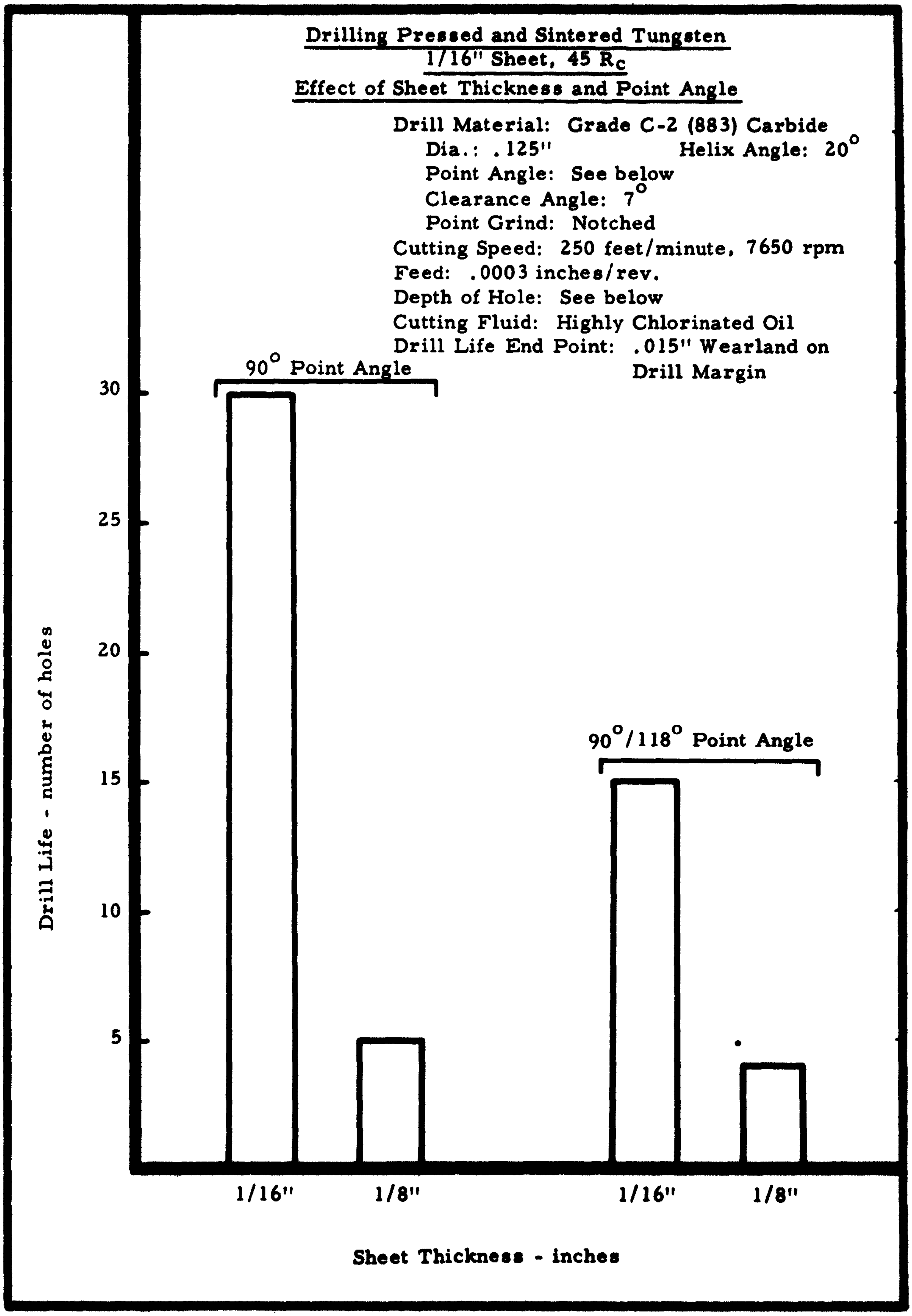


See Text page 16 Figure 10



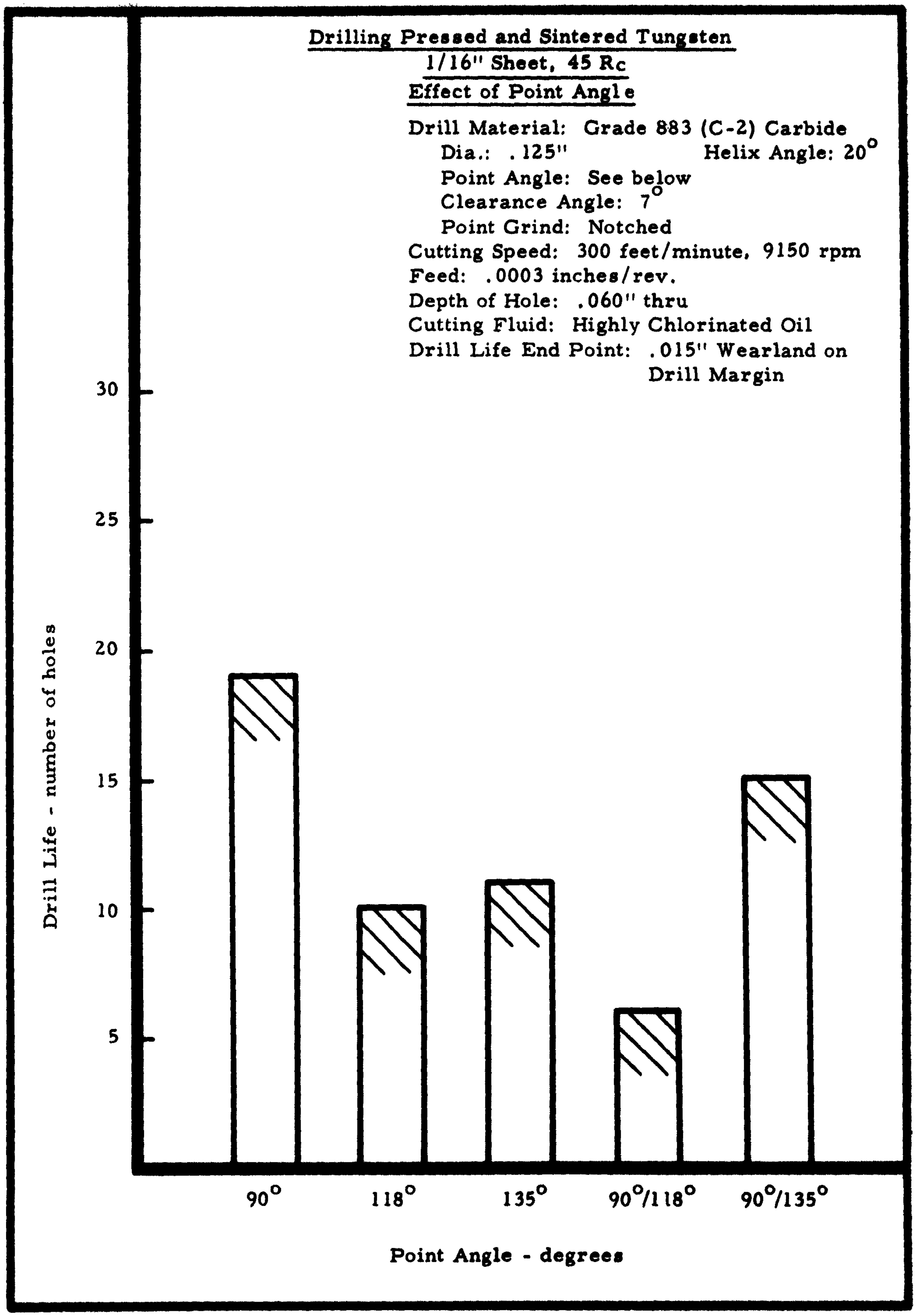
See Text page 17

Figure 11



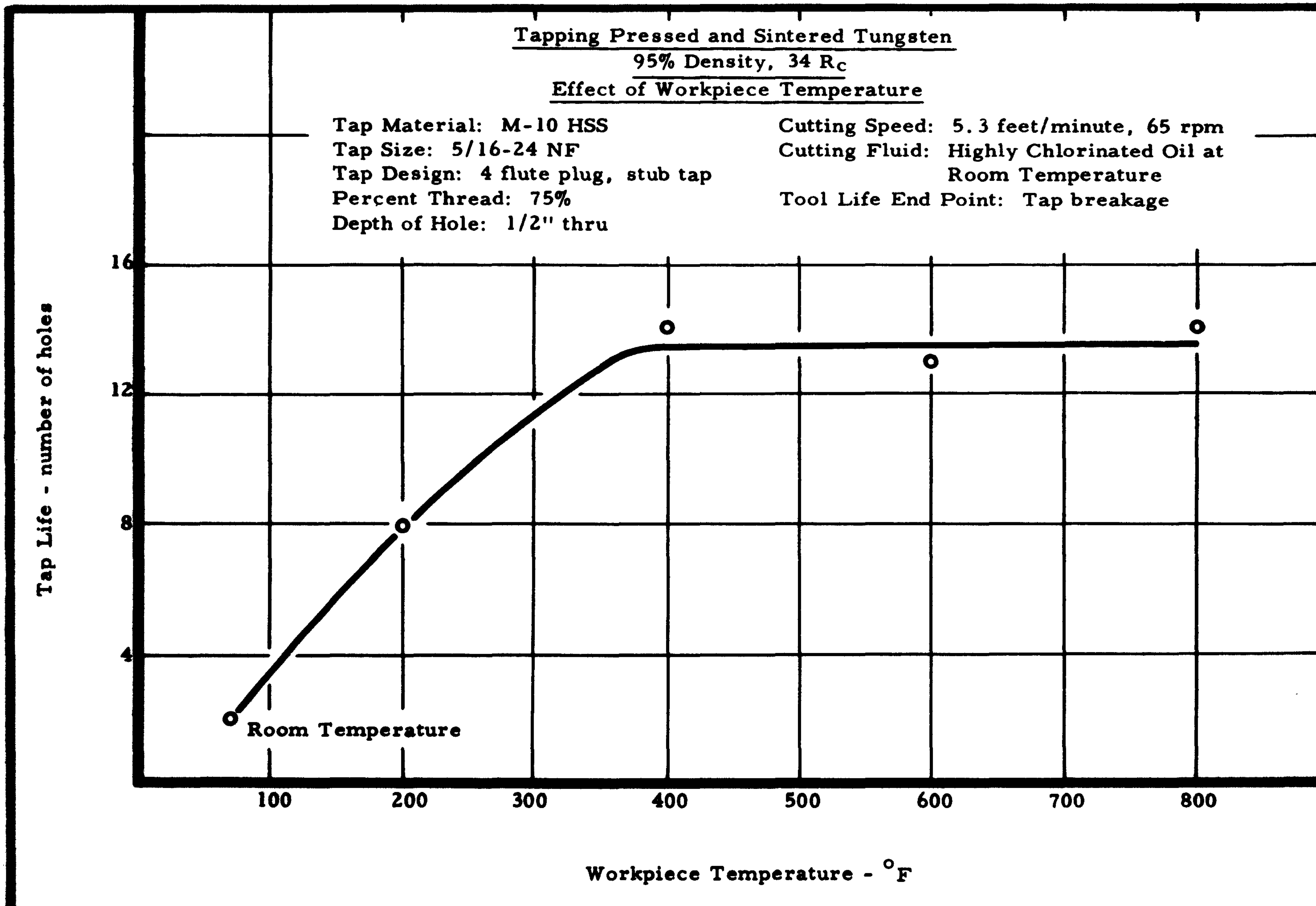
See Text page 17

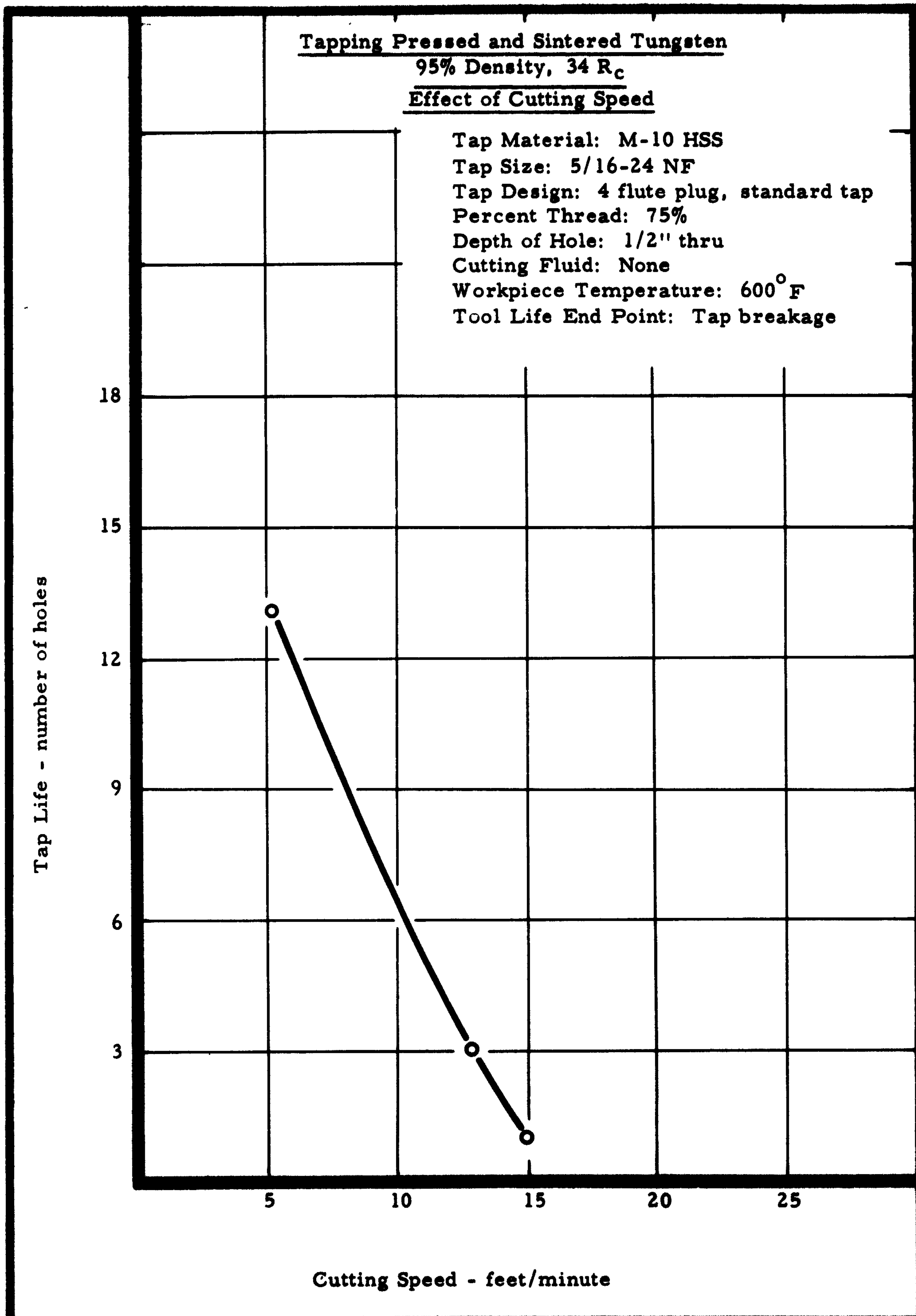
Figure 12



See Text page 17

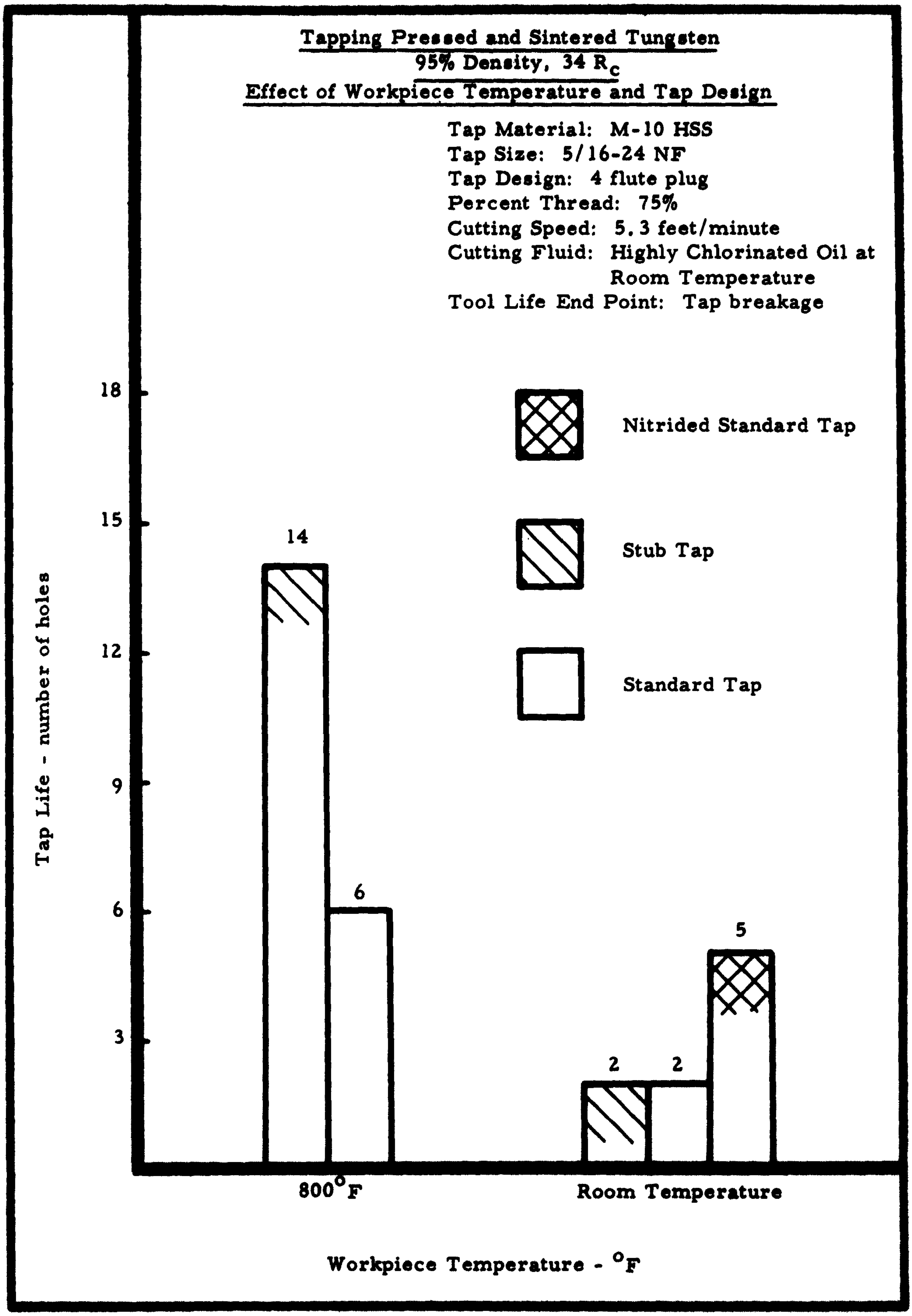
Figure 13


Tapping Pressed and Sintered Tungsten
95% Density, 34 R_c
Effect of Workpiece Temperature
Tap Material: M-10 HSS
Tap Size: 5/16-24 NF
Tap Design: 4 flute plug, stub tap
Percent Thread: 75%
Depth of Hole: 1/2" thru
Cutting Speed: 5.3 feet/minute, 65 rpm
Cutting Fluid: Highly Chlorinated Oil at Room Temperature
Tool Life End Point: Tap breakage
Tap Life - number of holes
16
12
8
4
Room Temperature
100
200
300
400
500
600
700
800
Workpiece Temperature - °F



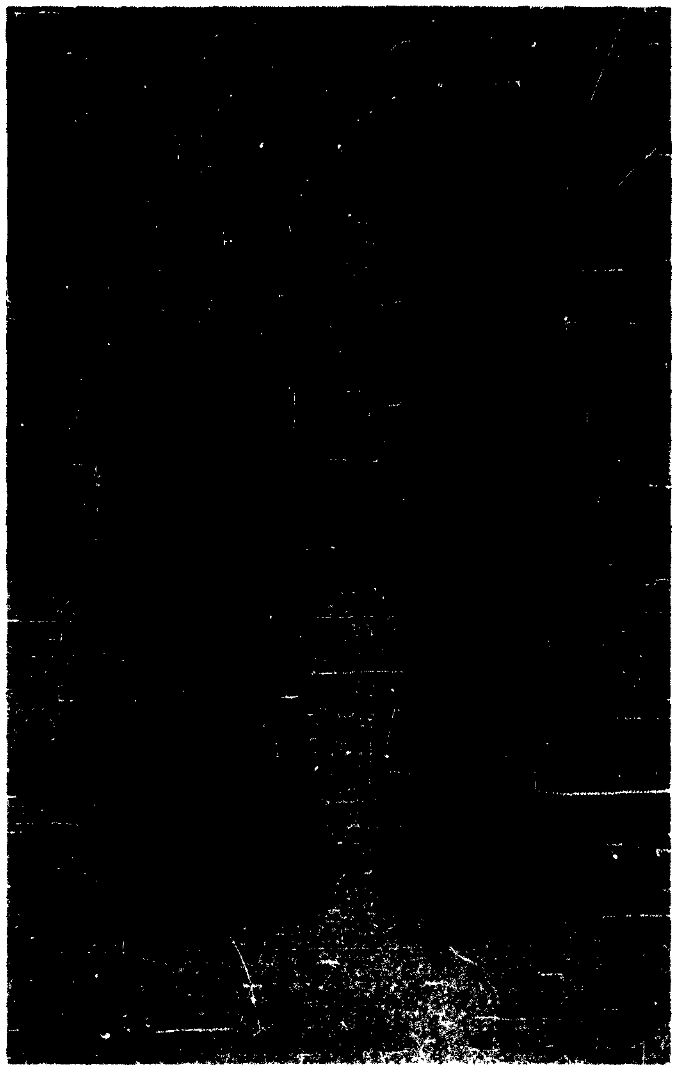
See Text page 18

Figure 15



See Text page 18

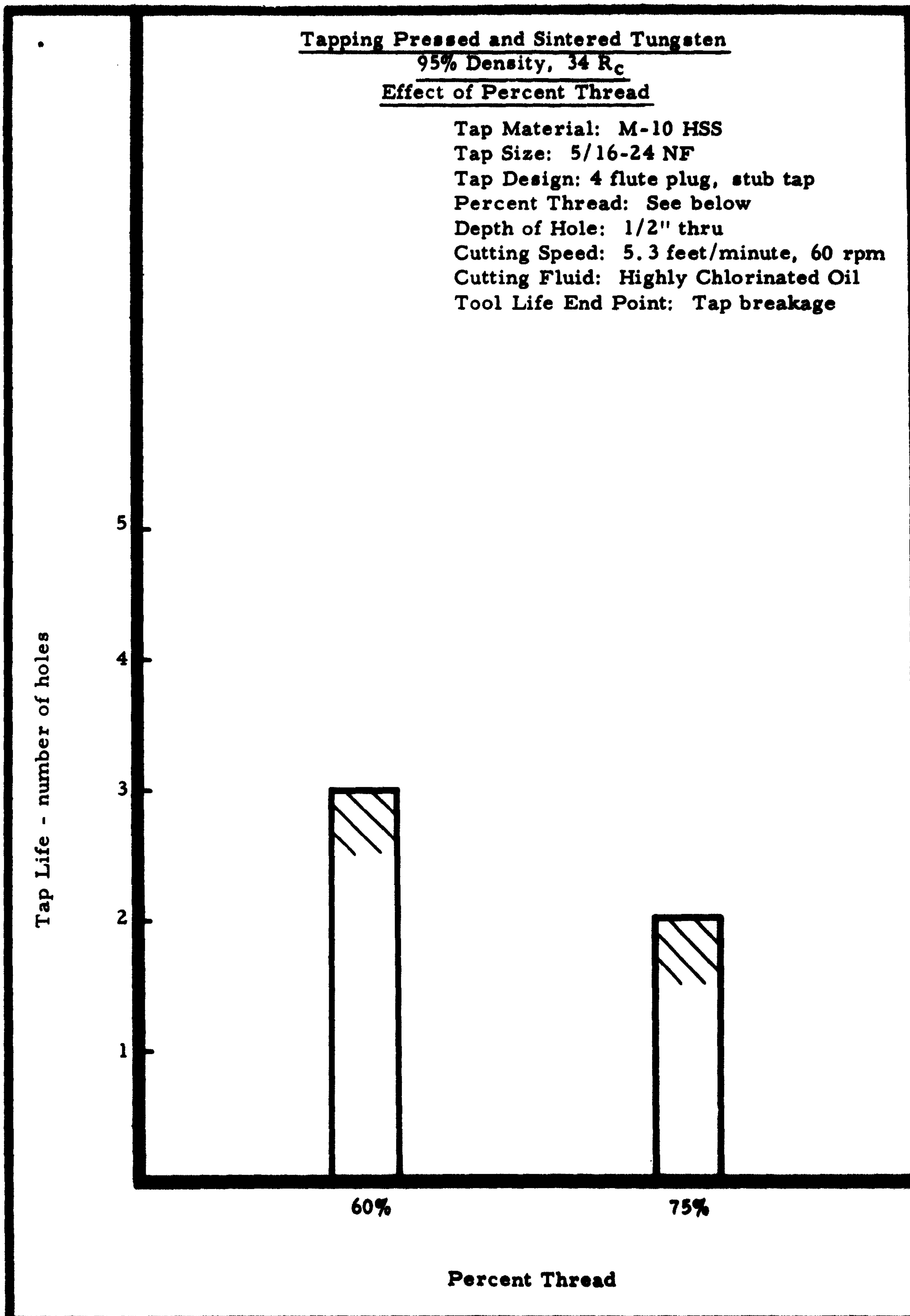
Figure 16



Special stub length type M-10 HSS tap (2" long) and standard length type M-10 HSS tap (2-3/4" long) used in tapping pressed and sintered tungsten. The maximum depth of hole that can be tapped with the special stub length tap is 1/2".

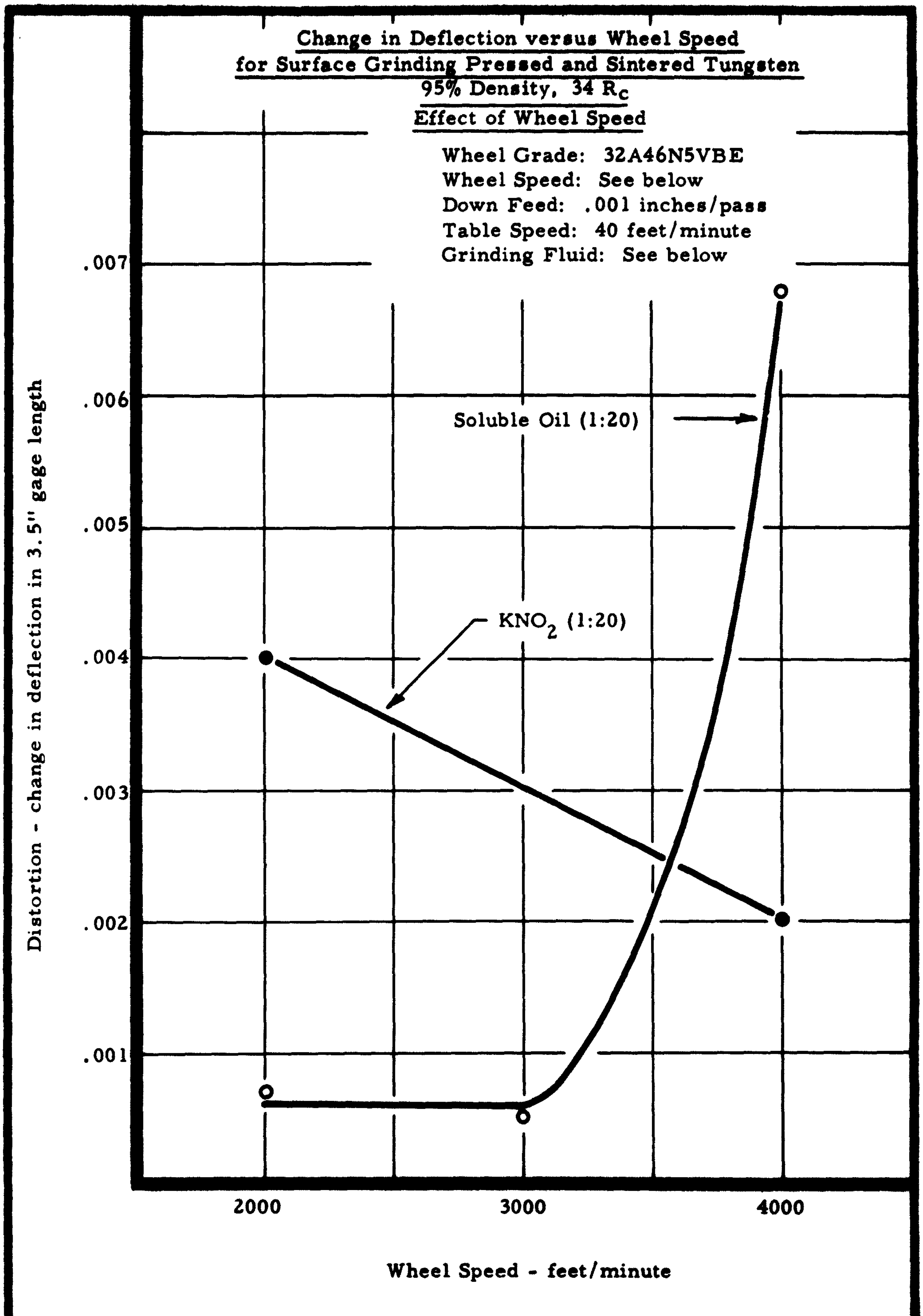
See text page 18.

Figure 17

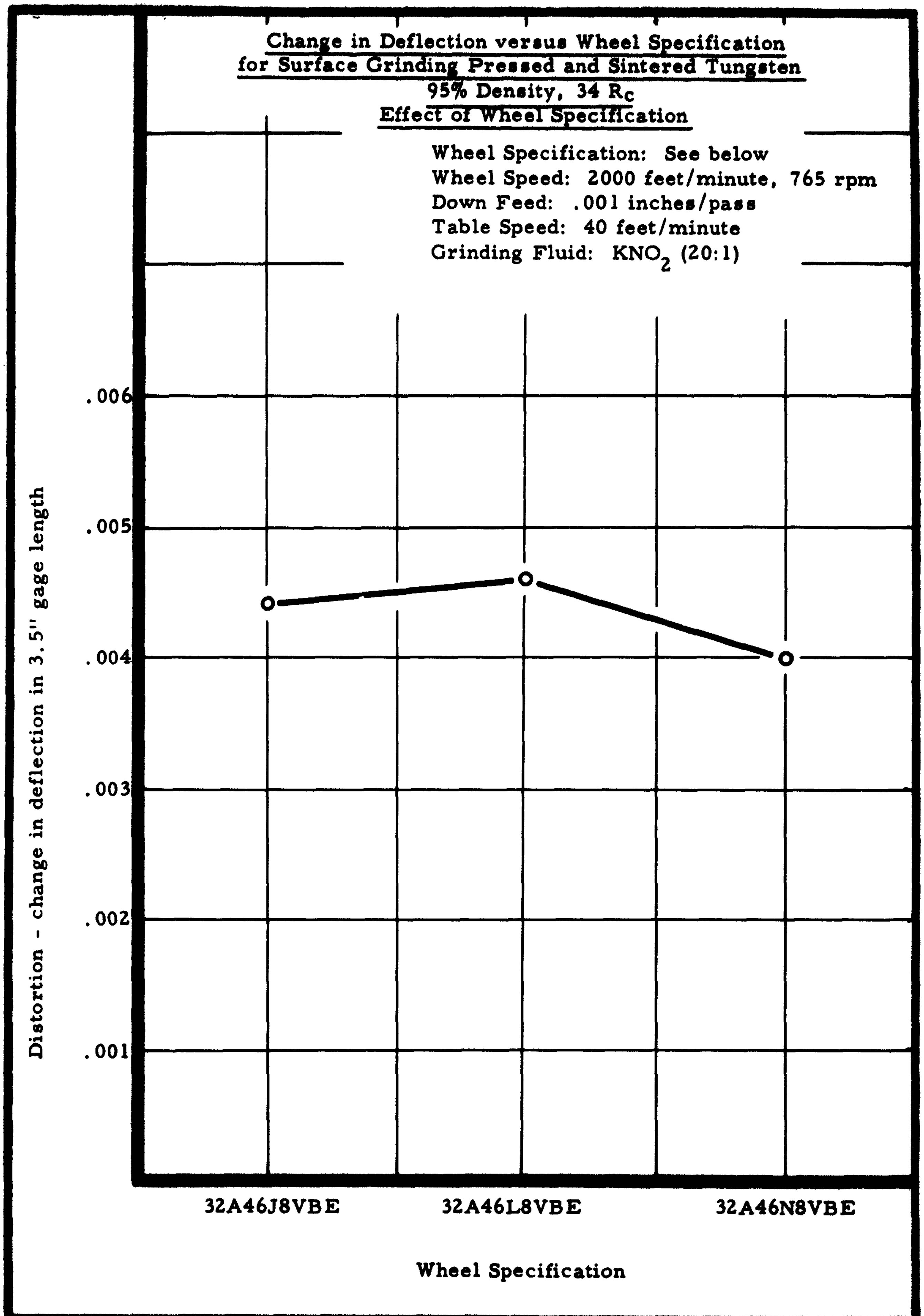


See Text page 18

Figure 18

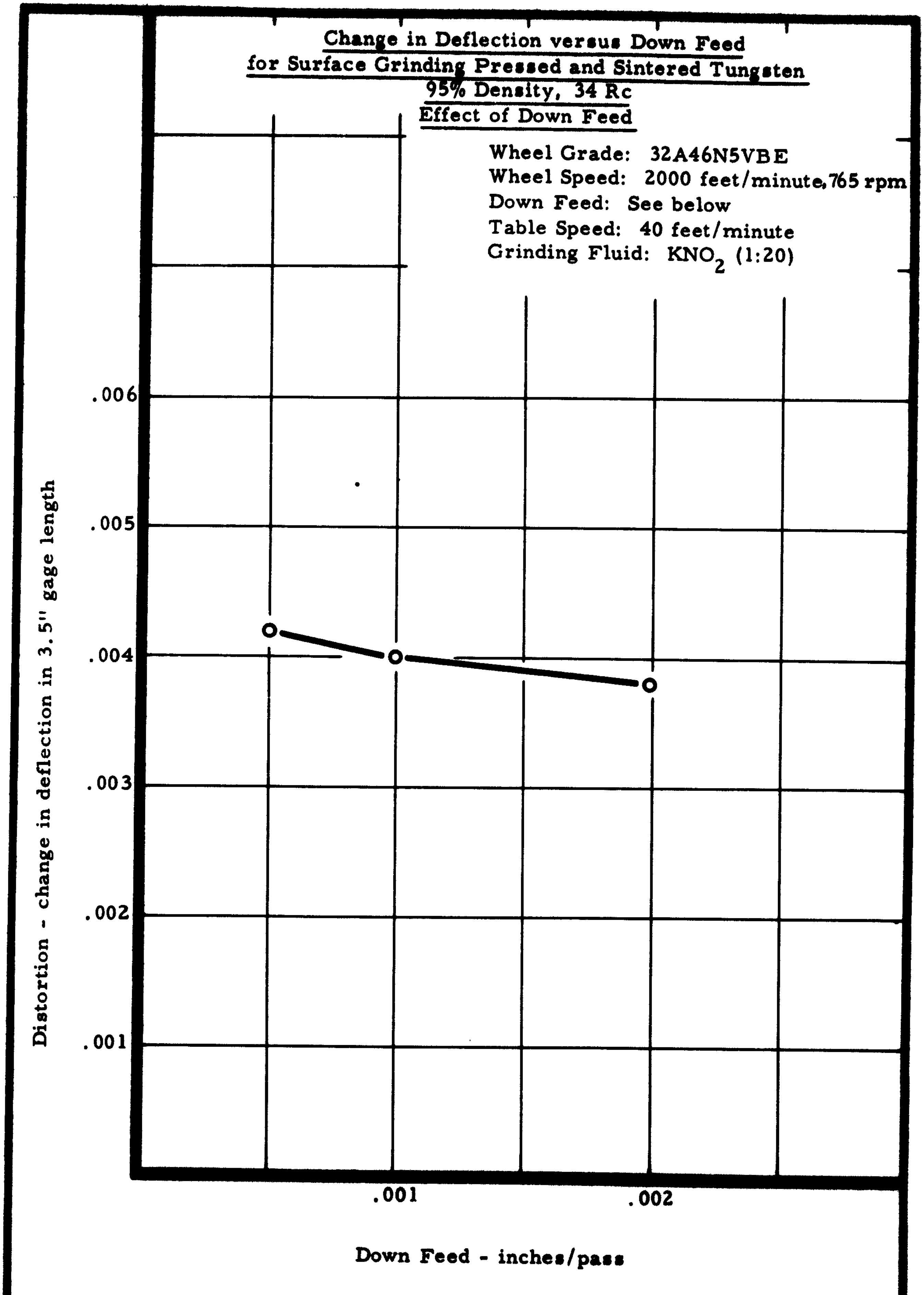


See Text page 18 Figure 19



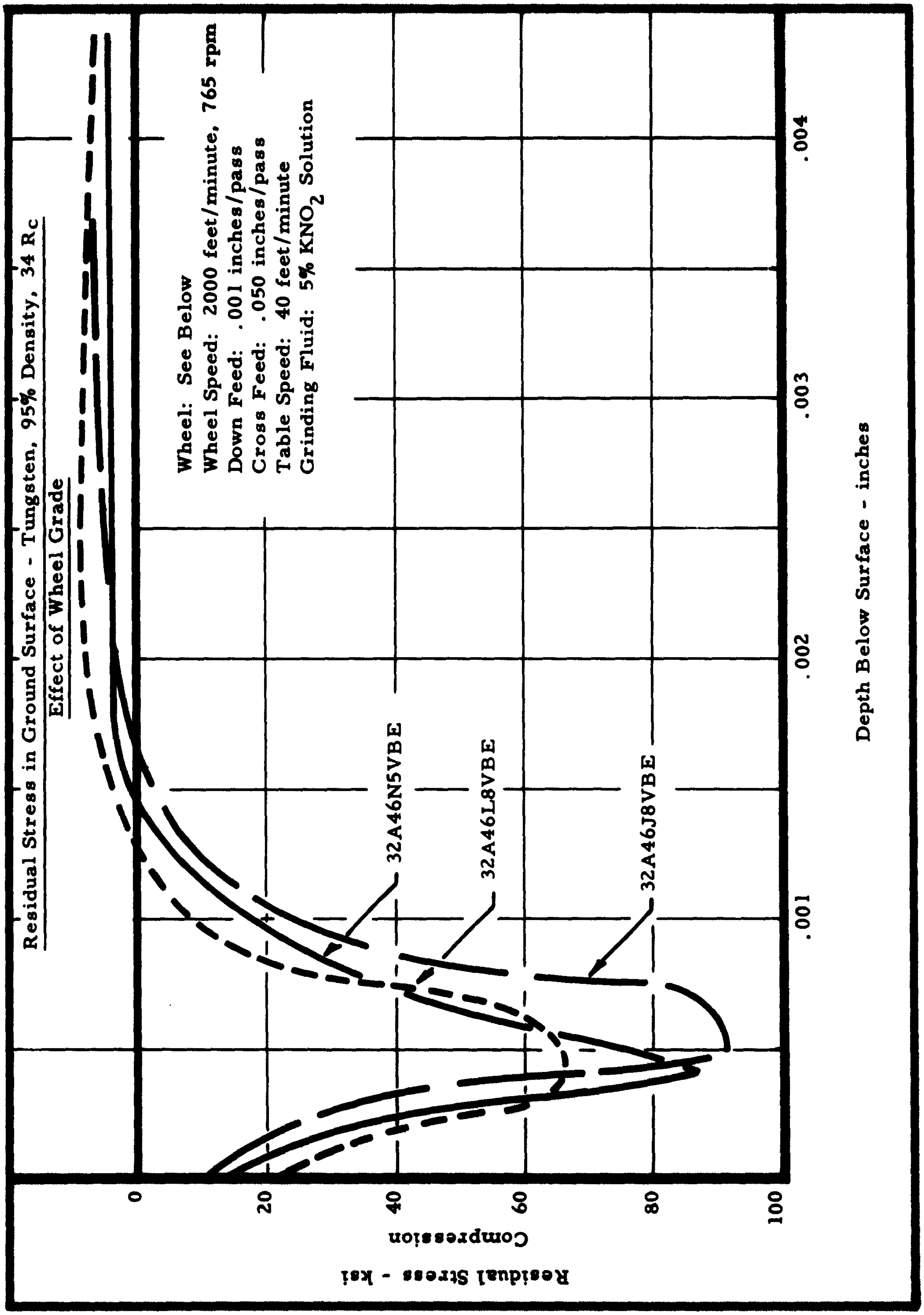
See Text page 19

Figure 20



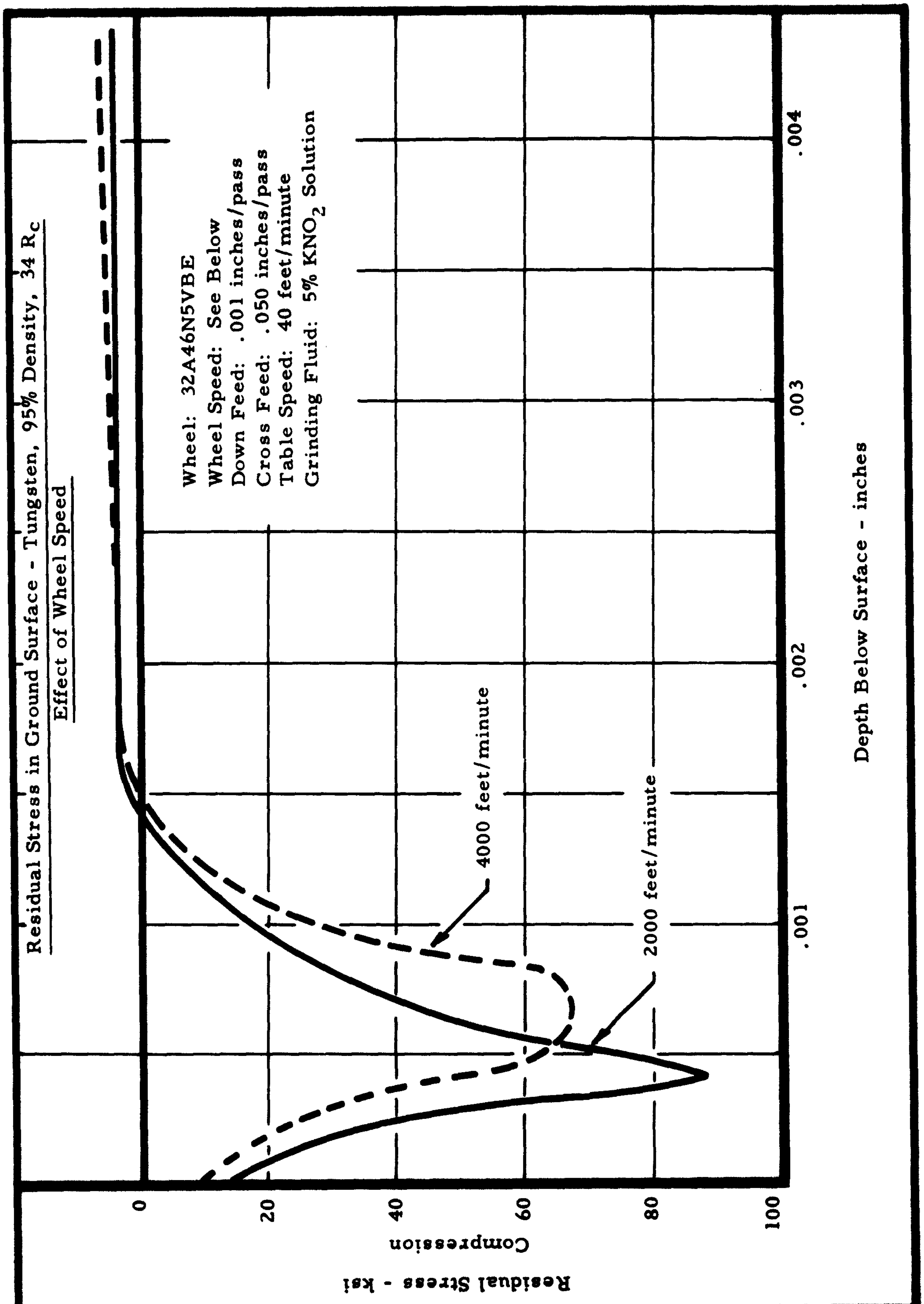
See Text page 19

Figure 21



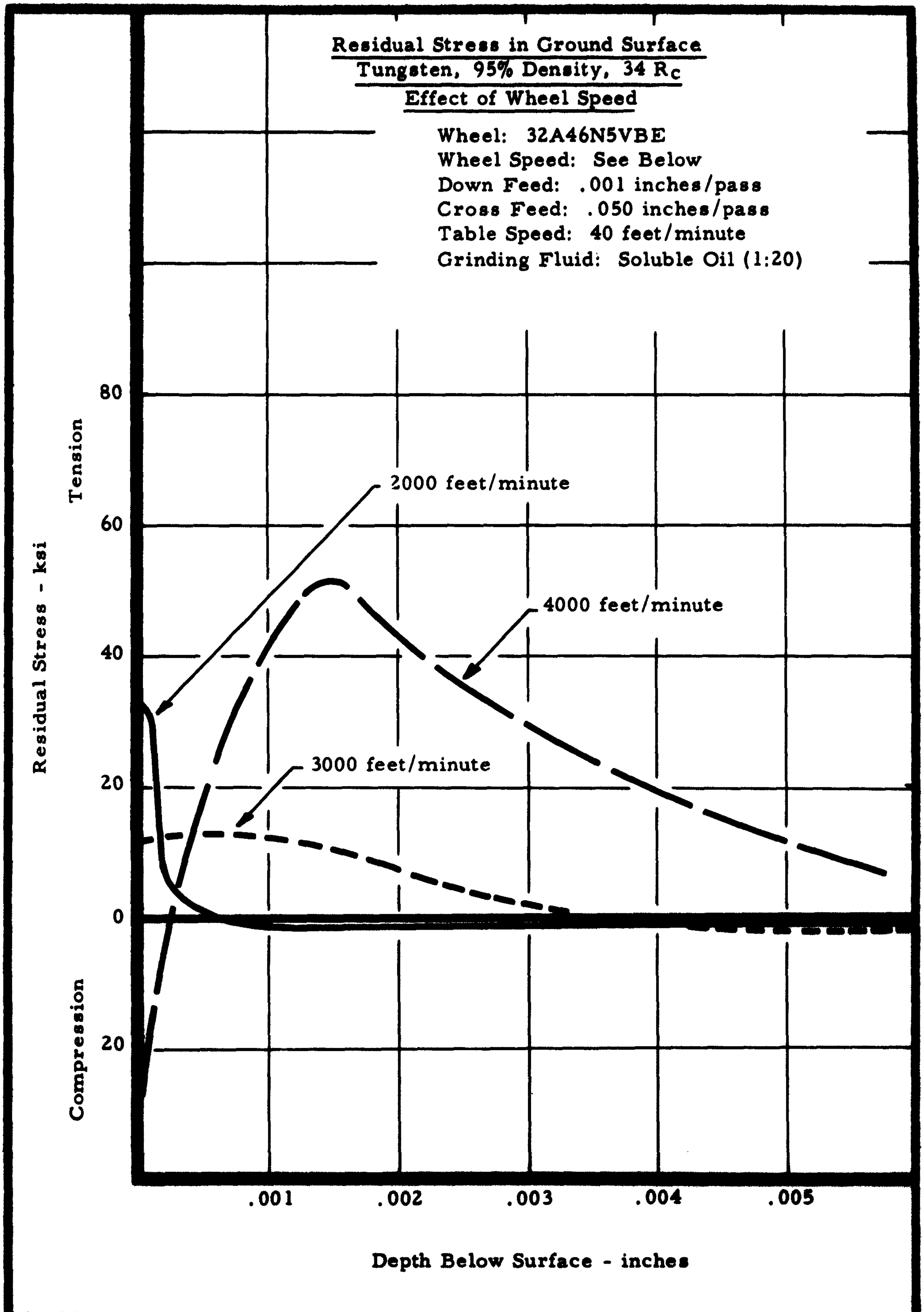
See Text page 19

Figure 22



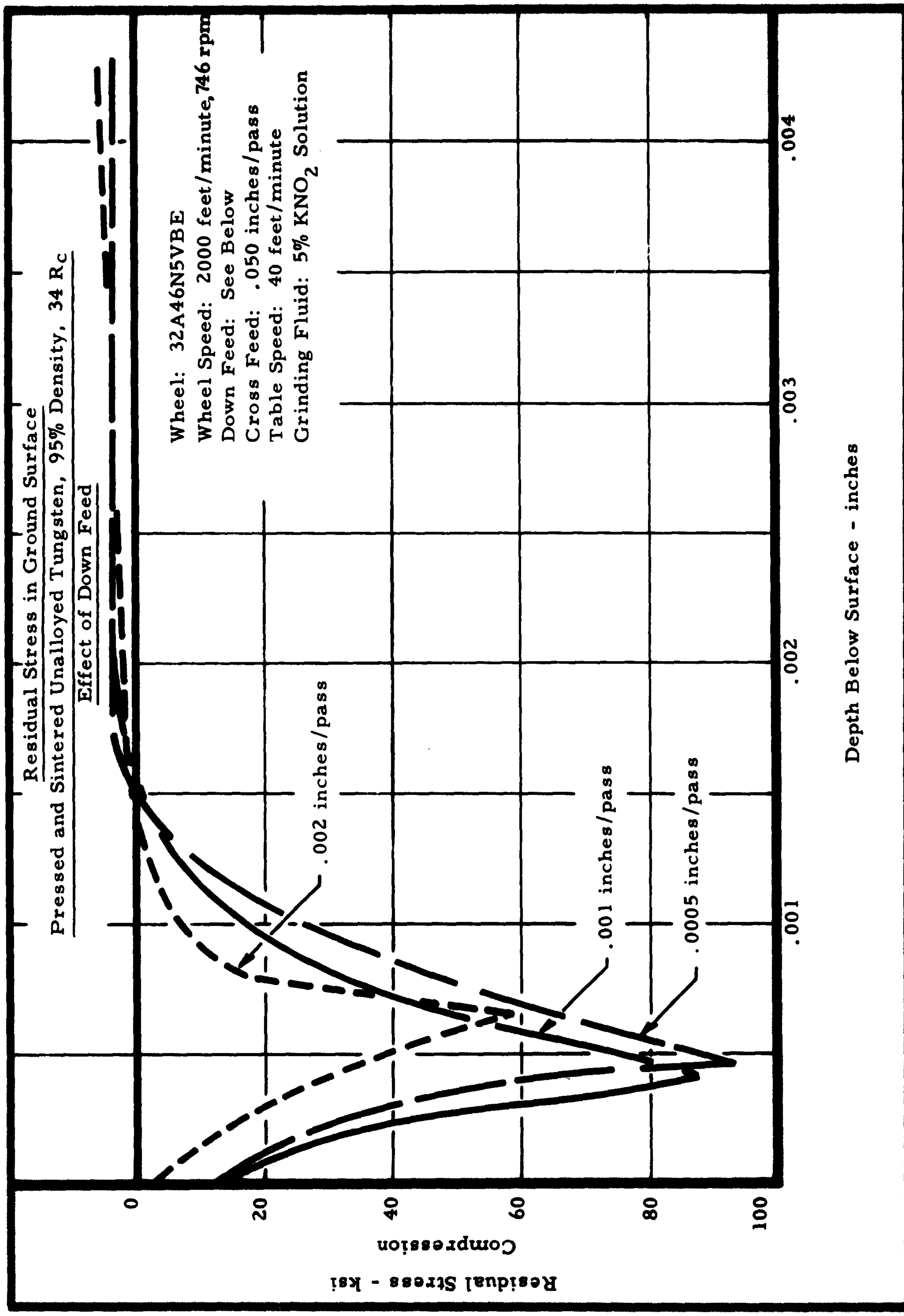
See Text page 20

Figure 23



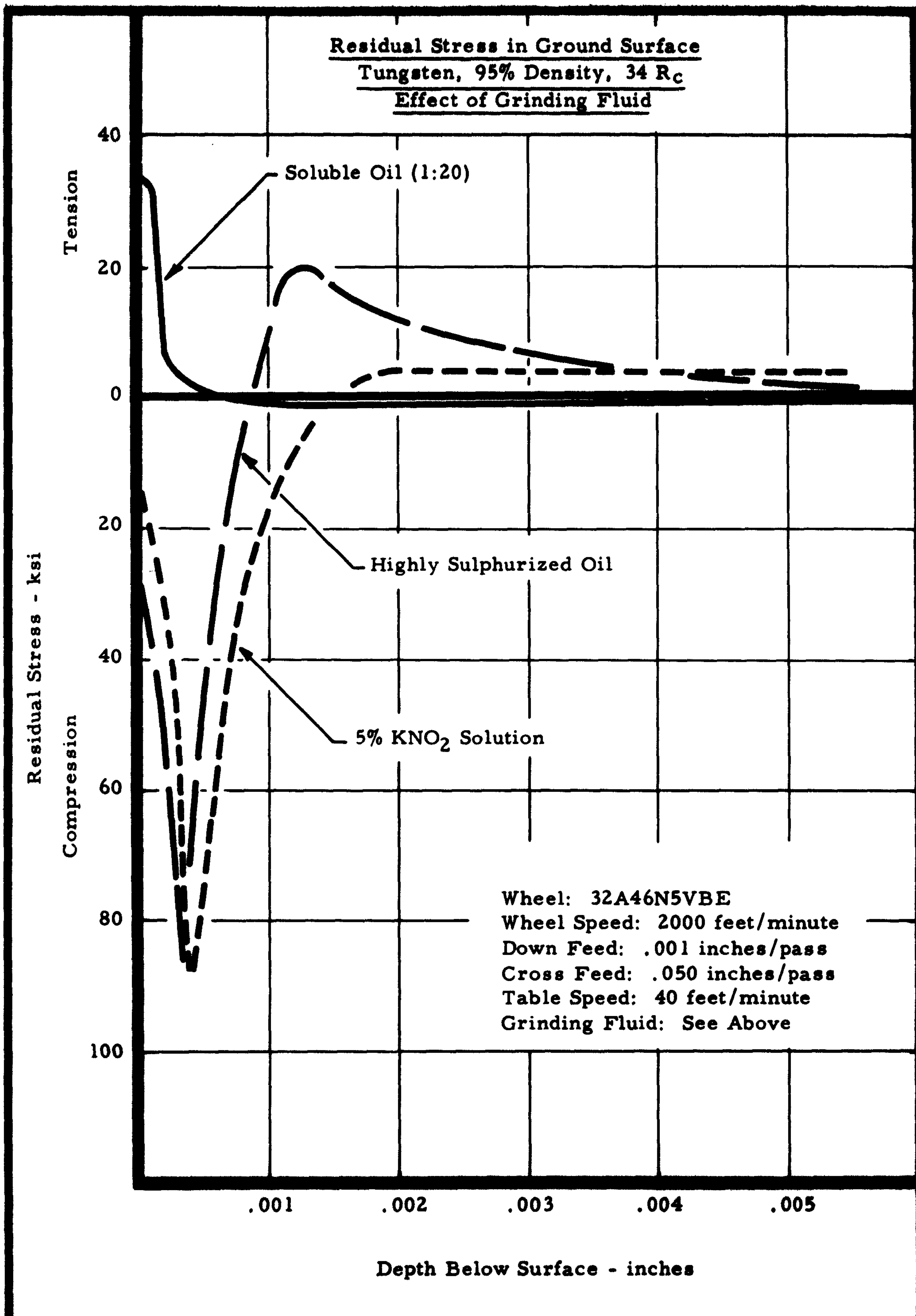
See Text page 20

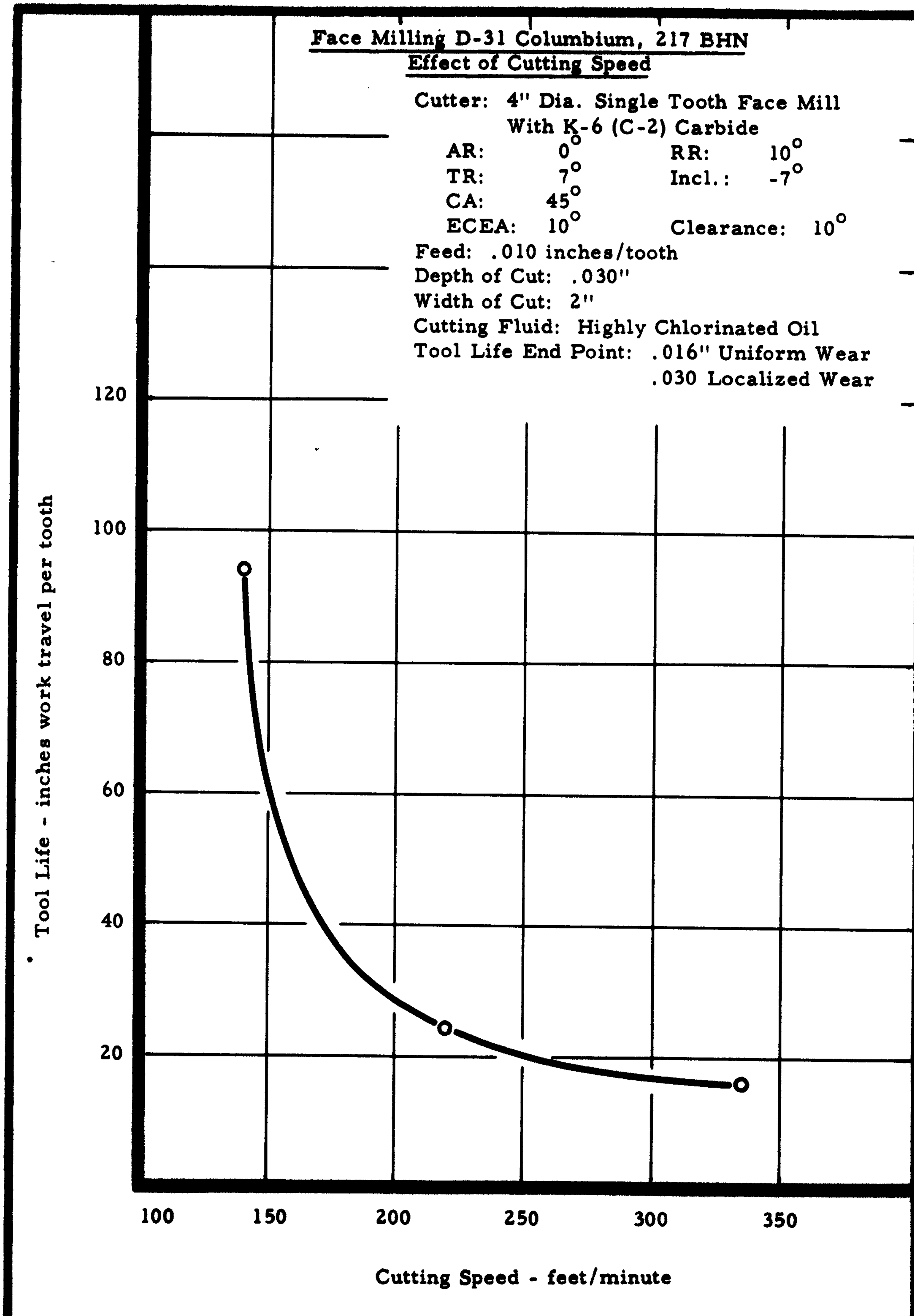
Figure 24



See Text page 20

Figure 25


Residual Stress in Ground Surface
Tungsten, 95% Density, 34 R_C
Effect of Grinding Fluid
Soluble Oil (1:20)
Highly Sulphurized Oil
5% KNO_2 Solution
Tension
Compression
Residual Stress - ksi
40
20
0
20
40
60
80
100
.001
.002
.003
.004
.005
Depth Below Surface - inches
Wheel: 32A46N5VBE
Wheel Speed: 2000 feet/minute
Down Feed: .001 inches/pass
Cross Feed: .050 inches/pass
Table Speed: 40 feet/minute
Grinding Fluid: See Above



See Text page 21

Figure 27

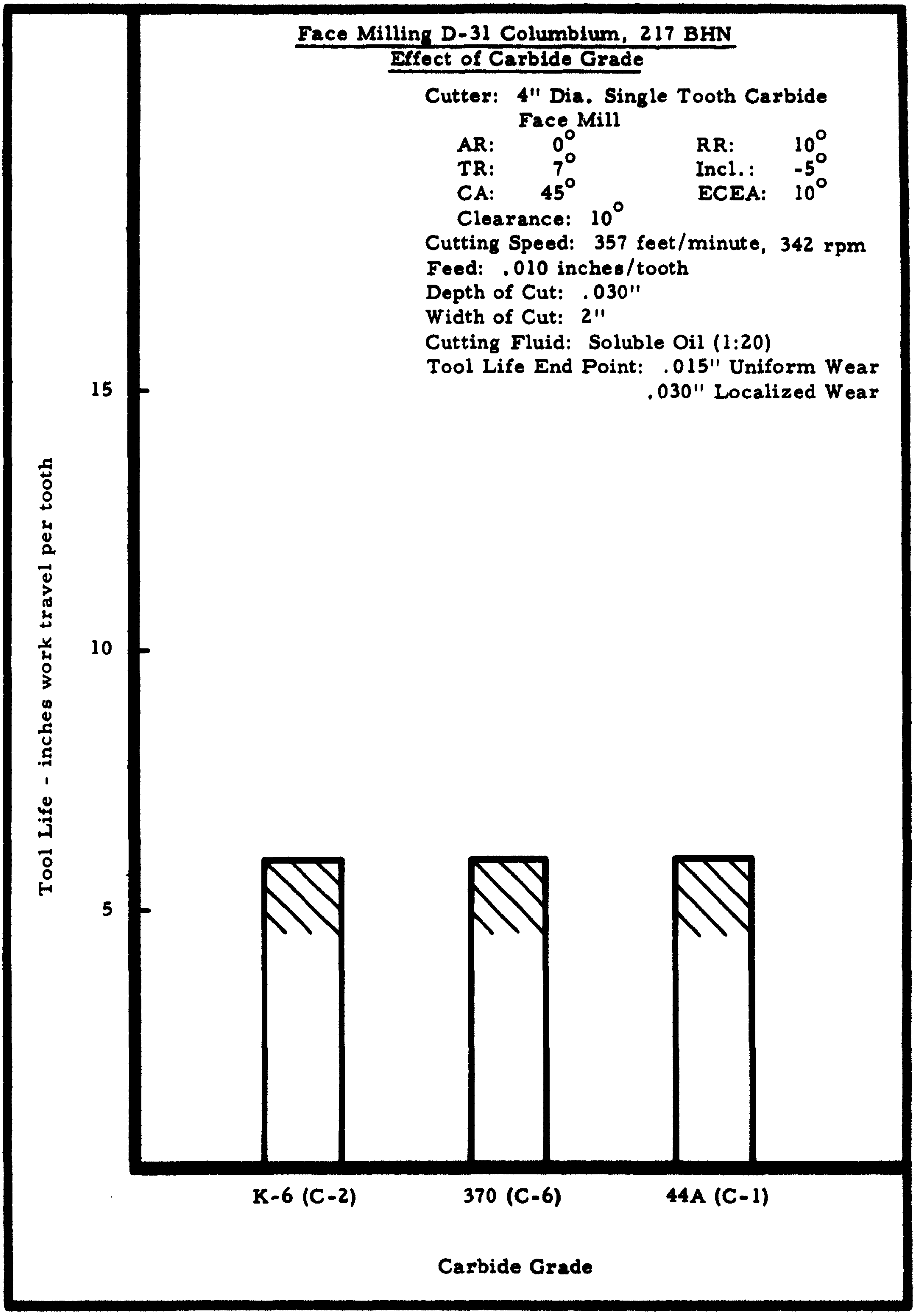
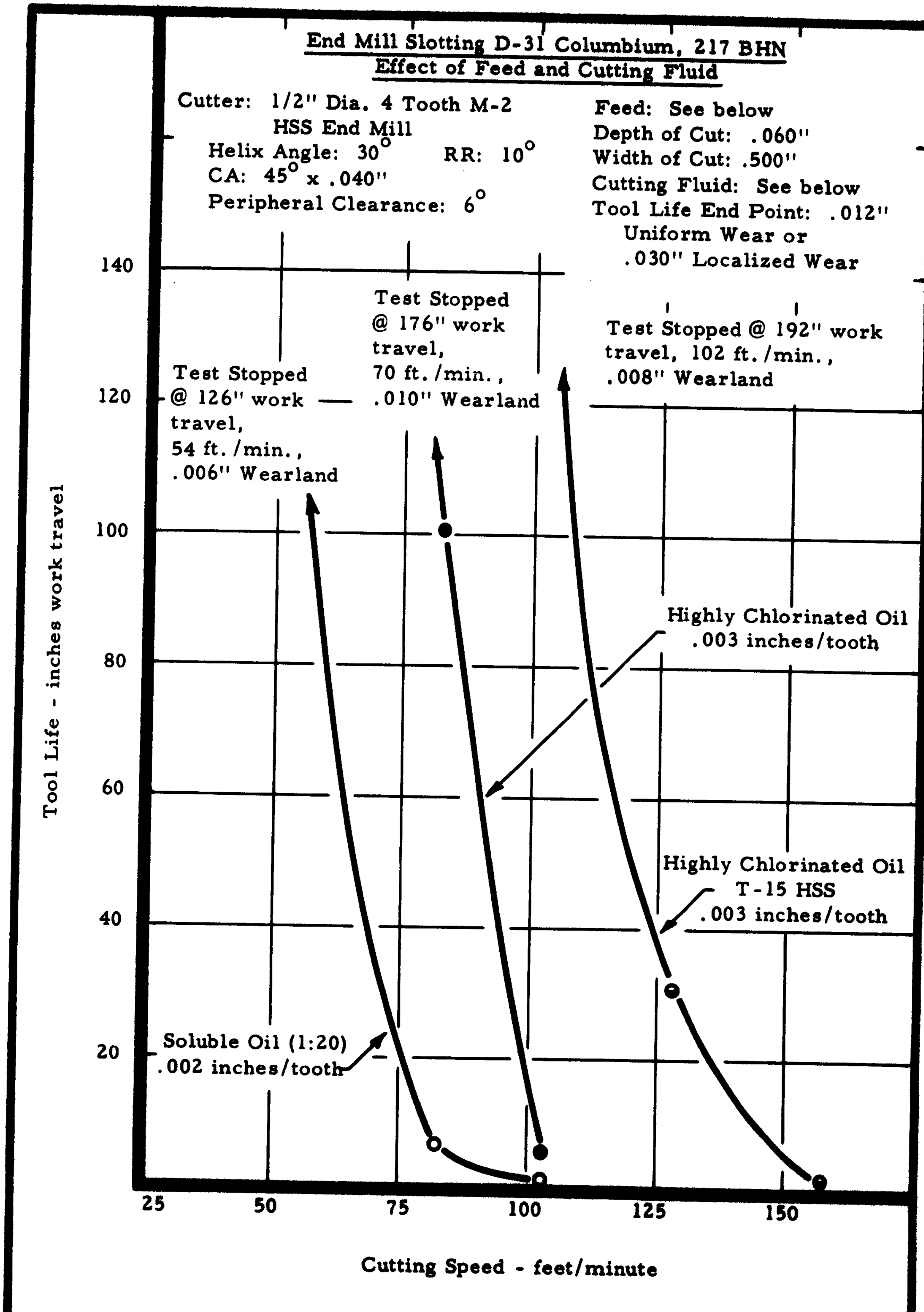
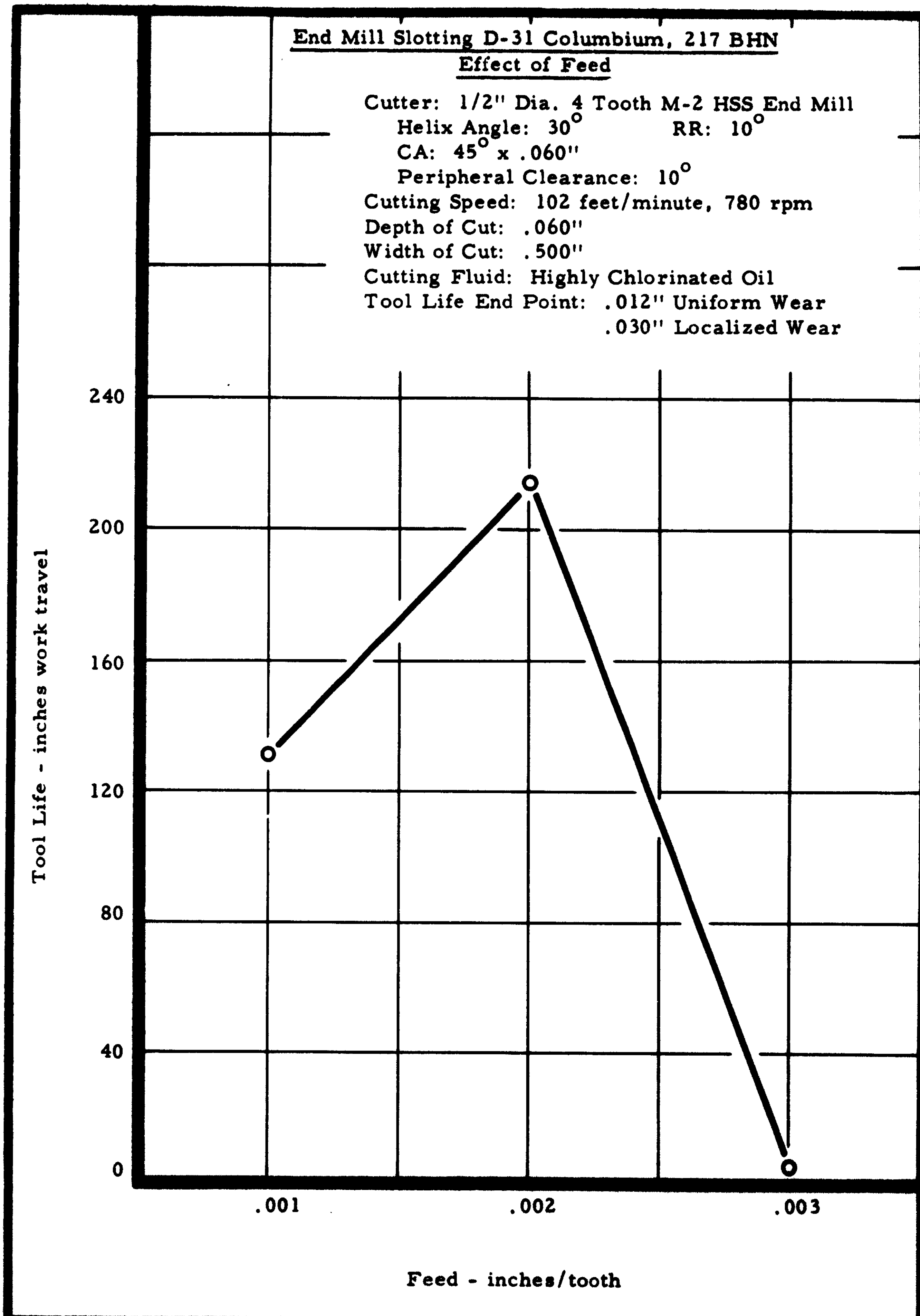

Face Milling D-31 Columbium, 217 BHN
Effect of Carbide Grade
Cutter: 4" Dia. Single Tooth Carbide Face Mill
AR: 0°
RR: 10°
TR: 7°
Incl.: -5°
CA: 45°
ECEA: 10°
Clearance: 10°
Cutting Speed: 357 feet/minute, 342 rpm
Feed: .010 inches/tooth
Depth of Cut: .030"
Width of Cut: 2"
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .015" Uniform Wear
.030" Localized Wear
15
10
5
Tool Life - inches work travel per tooth
K-6 (C-2)
370 (C-6)
44A (C-1)
Carbide Grade

Figure 28



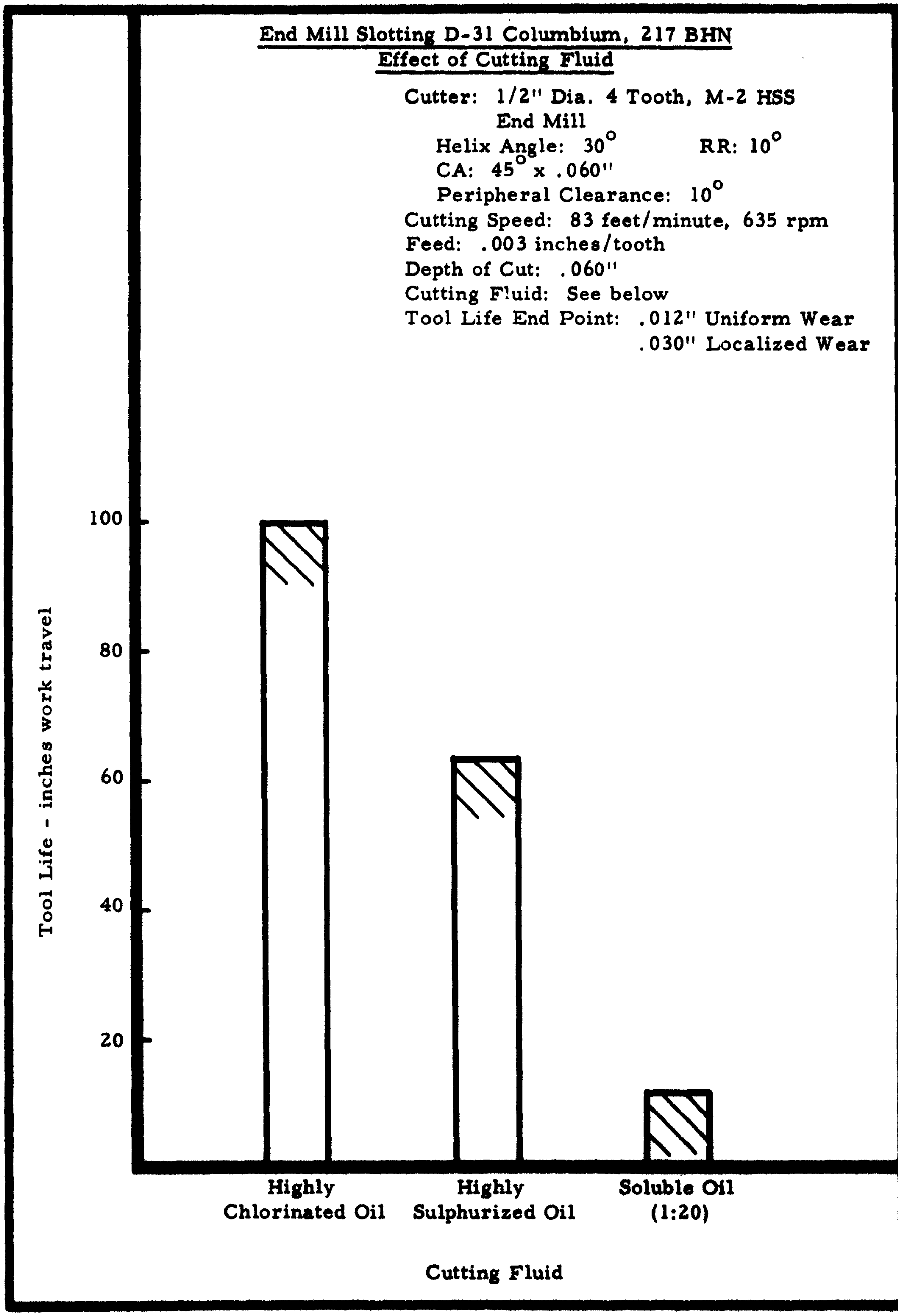
See Text page 21

Figure 29



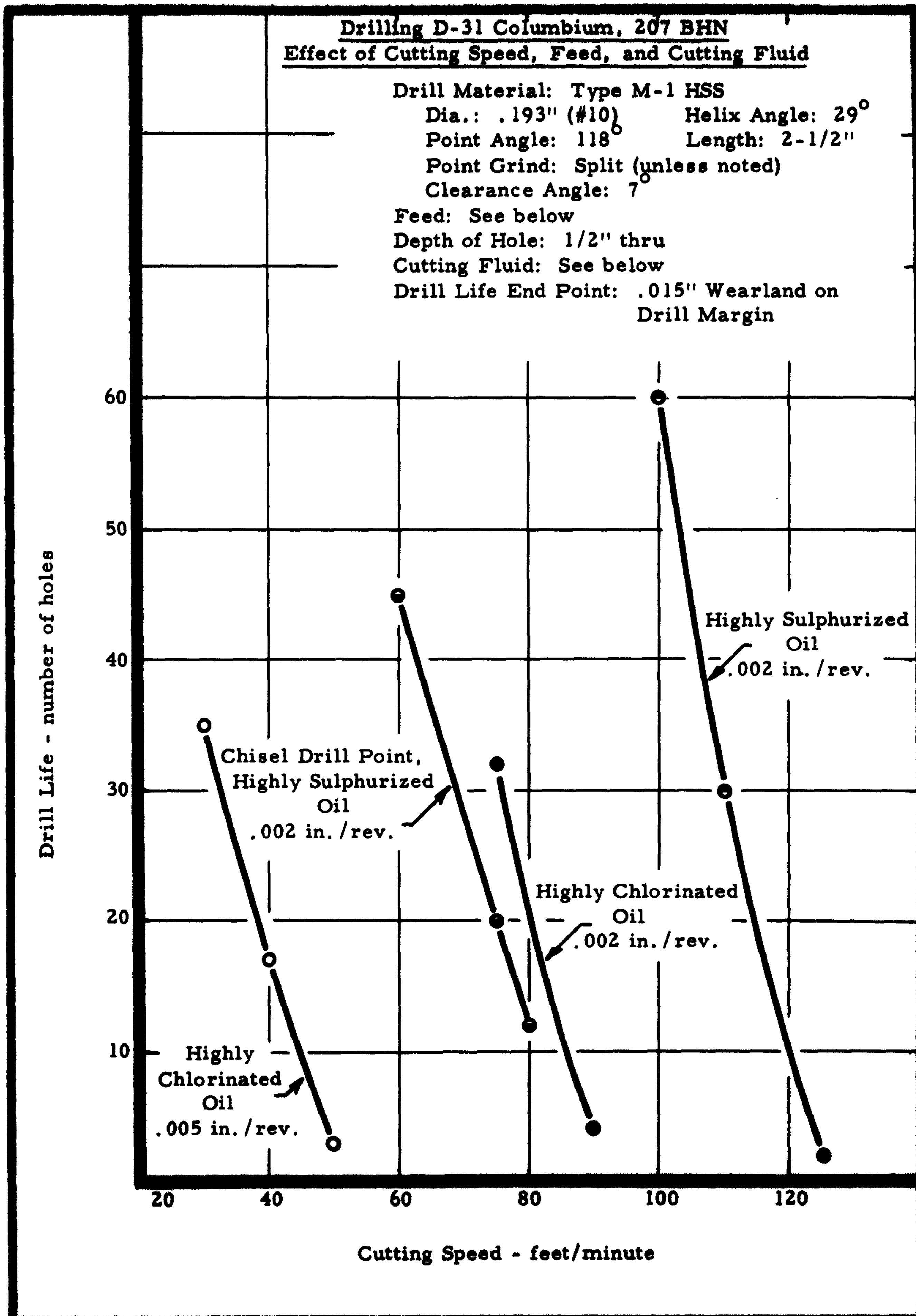
See Text page 22

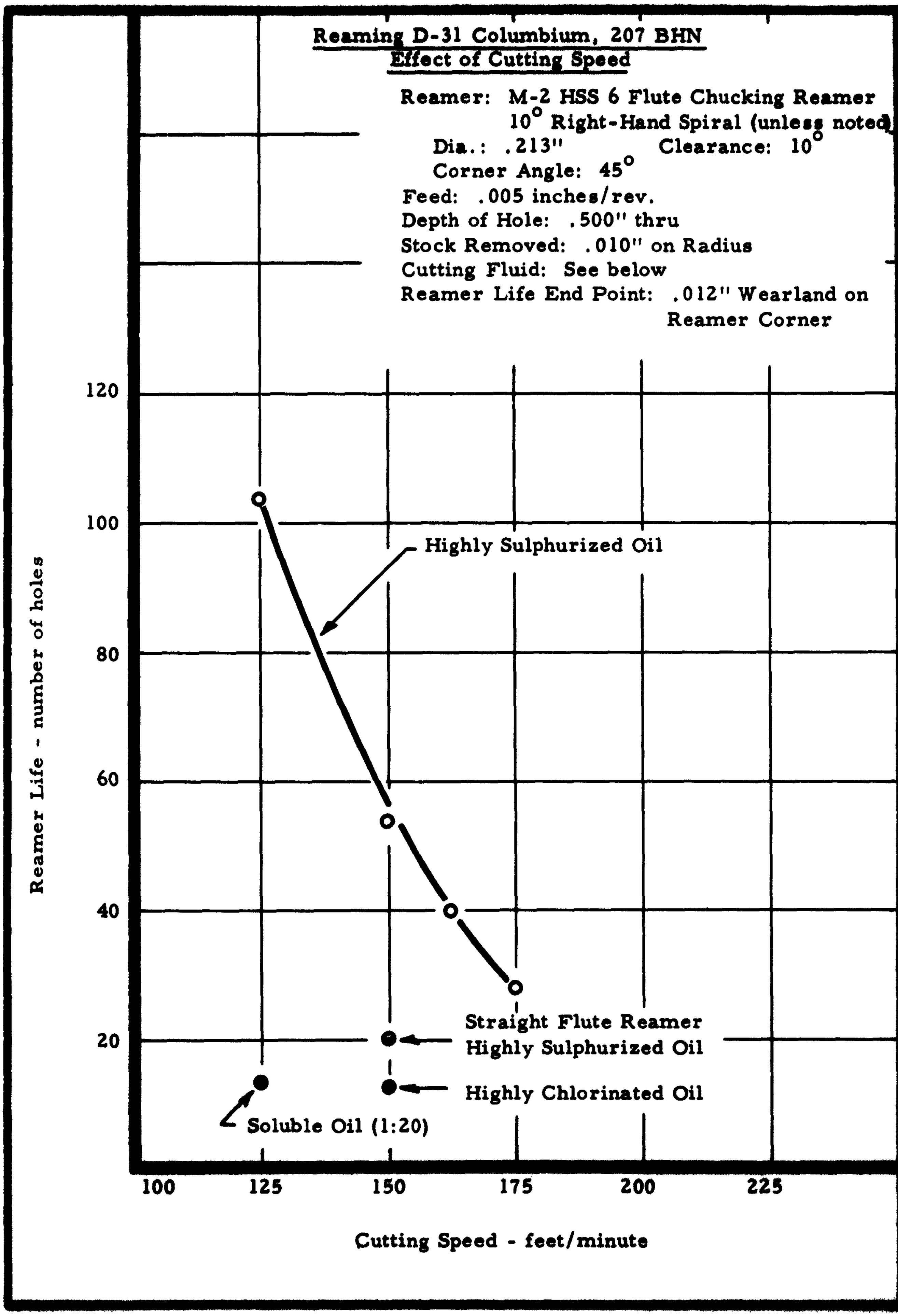
Figure 30



See Text page 22

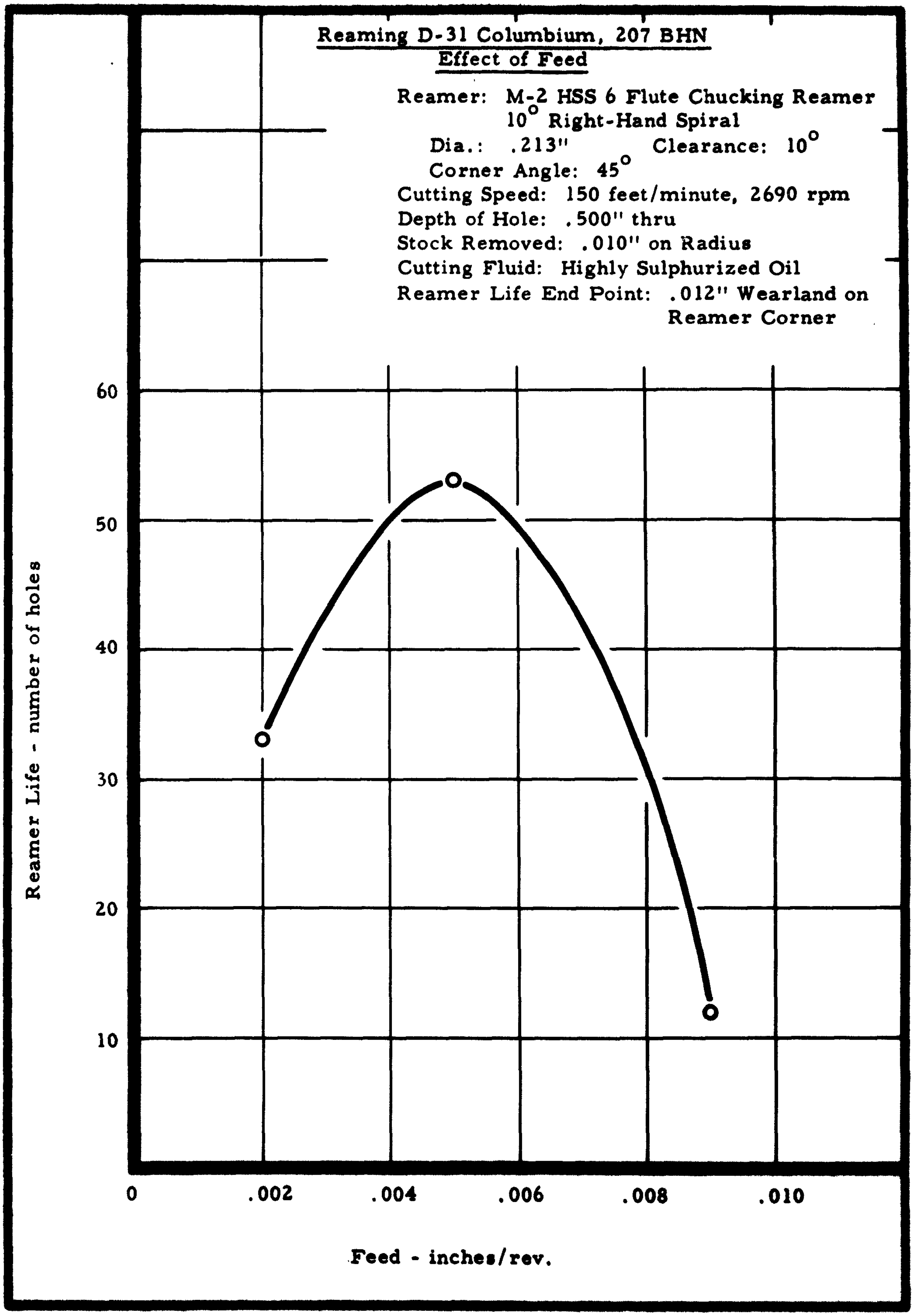
Figure 31


Drilling D-31 Columbium, 207 BHN
Effect of Cutting Speed, Feed, and Cutting Fluid
Drill Material: Type M-1 HSS
Dia.: .193" (#10)
Helix Angle: 29°
Point Angle: 118°
Length: 2-1/2"
Point Grind: Split (unless noted)
Clearance Angle: 7°
Feed: See below
Depth of Hole: 1/2" thru
Cutting Fluid: See below
Drill Life End Point: .015" Wearland on Drill Margin
Highly Sulphurized Oil .002 in./rev.
Chisel Drill Point, Highly Sulphurized Oil .002 in./rev.
Highly Chlorinated Oil .002 in./rev.
Highly Chlorinated Oil .005 in./rev.
Drill Life - number of holes
10
20
30
40
50
60
20
40
60
80
100
120
Cutting Speed - feet/minute



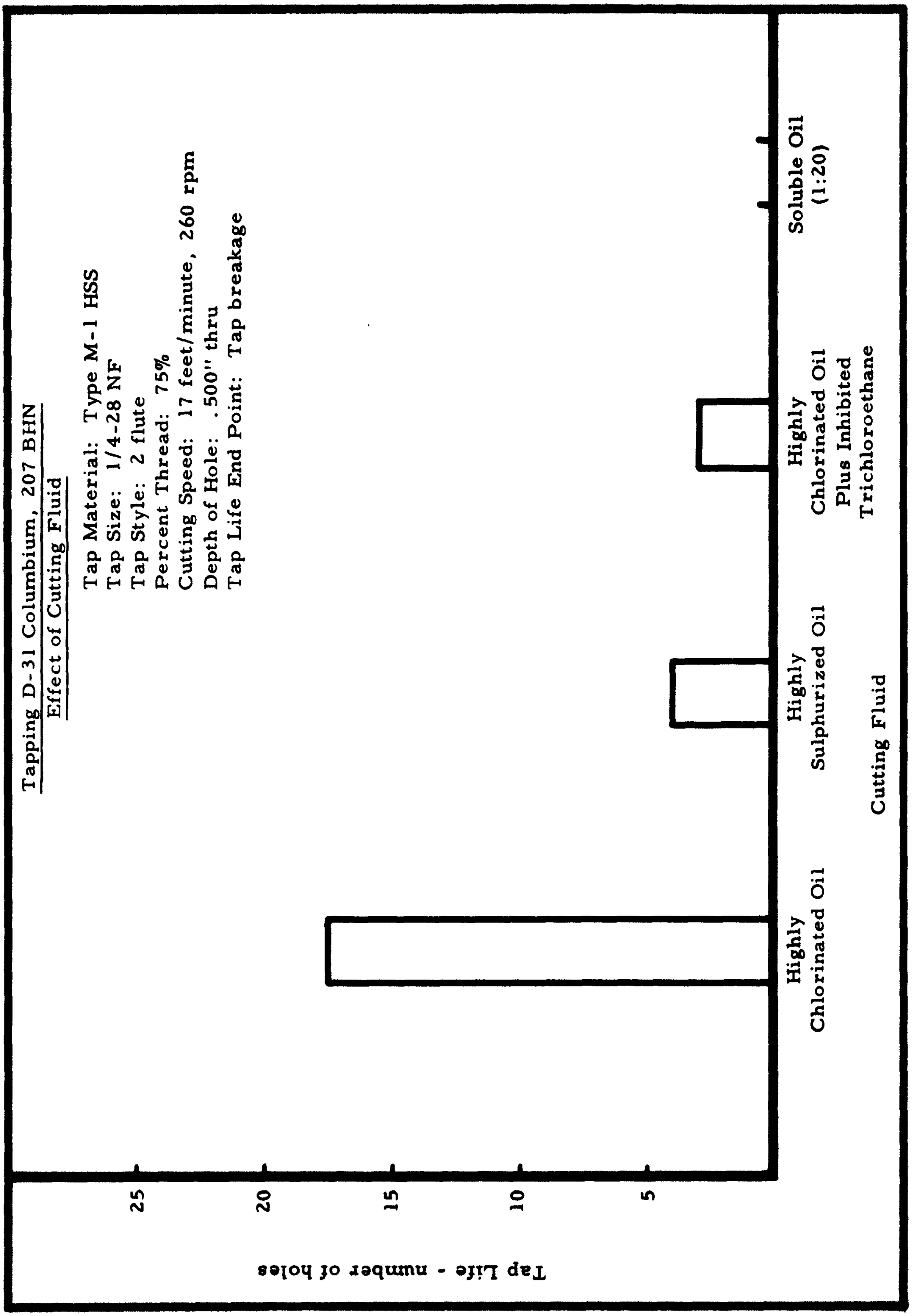
See Text page 22

Figure 33



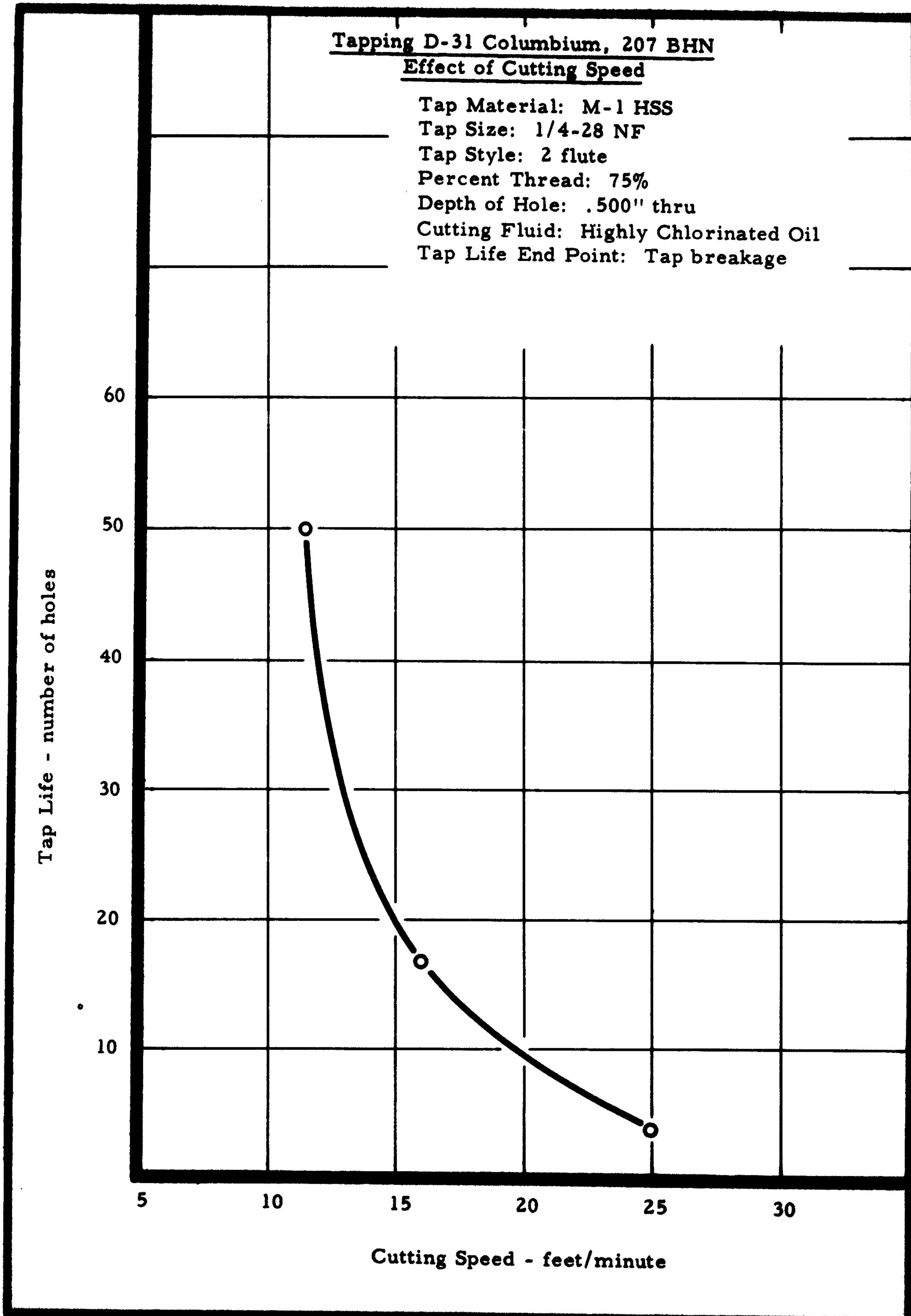
See Text page 22

Figure 34



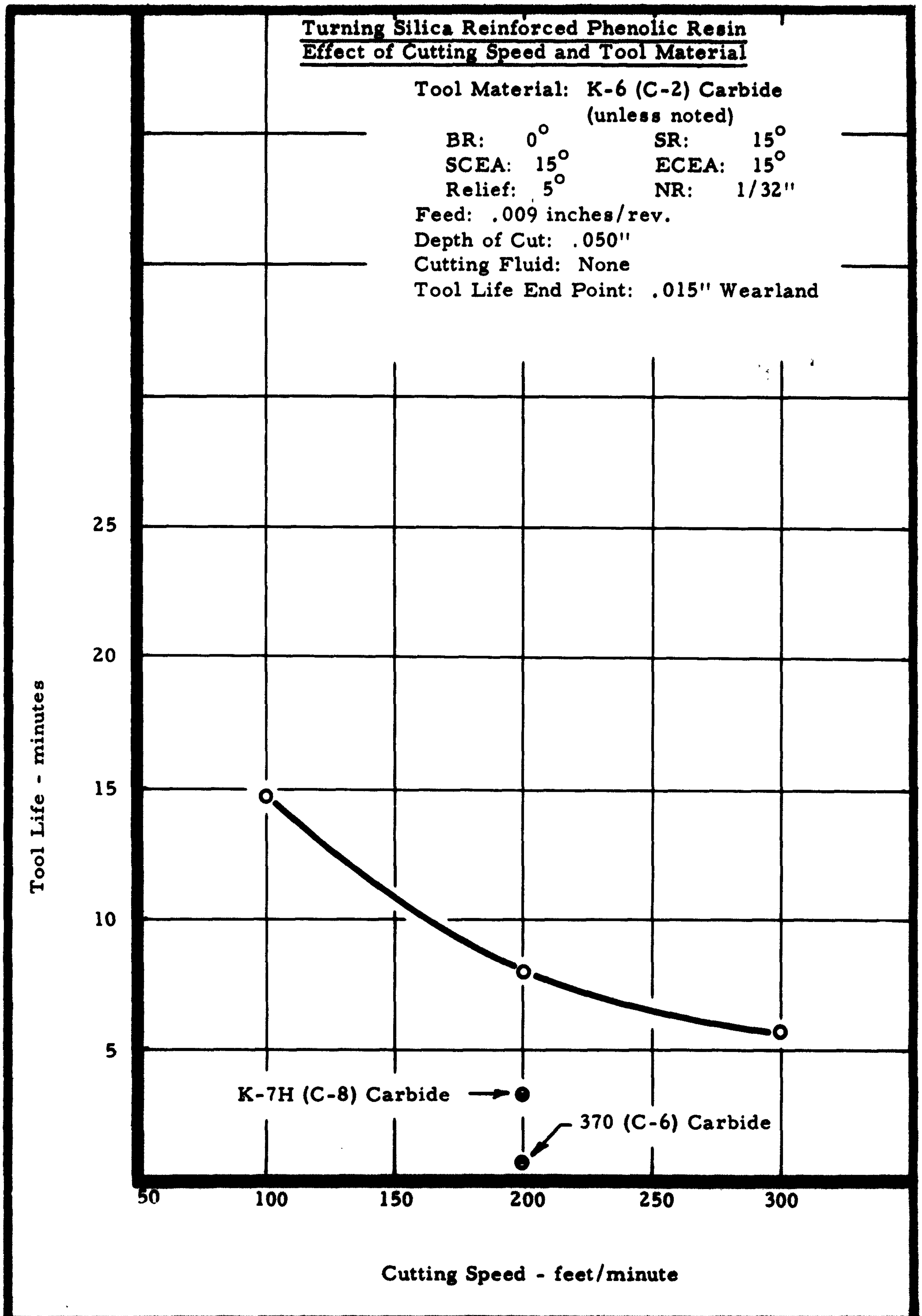
See Test page 23

Figure 35



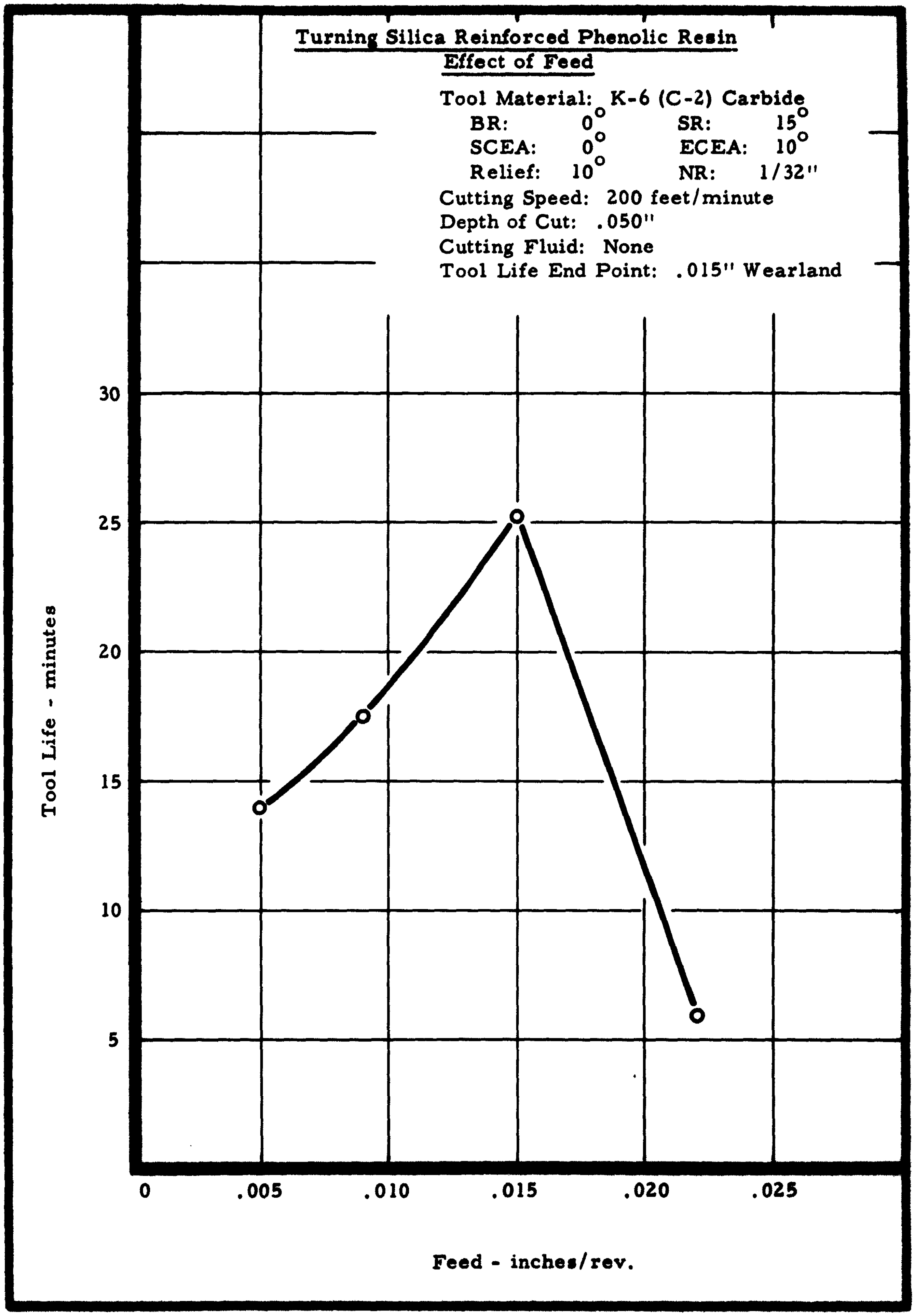
See Text page 23

Figure 36



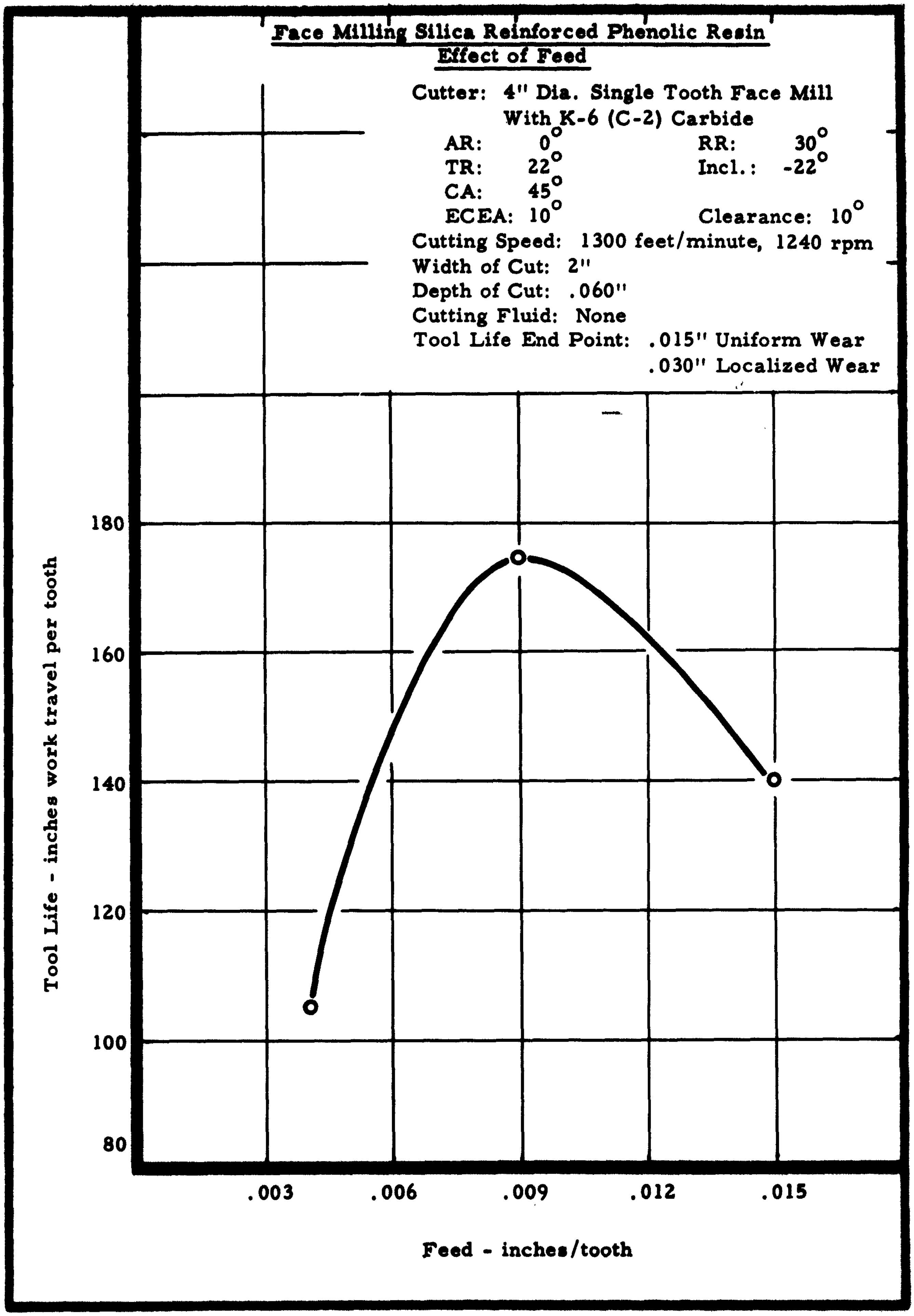
See Text page 23

Figure 37



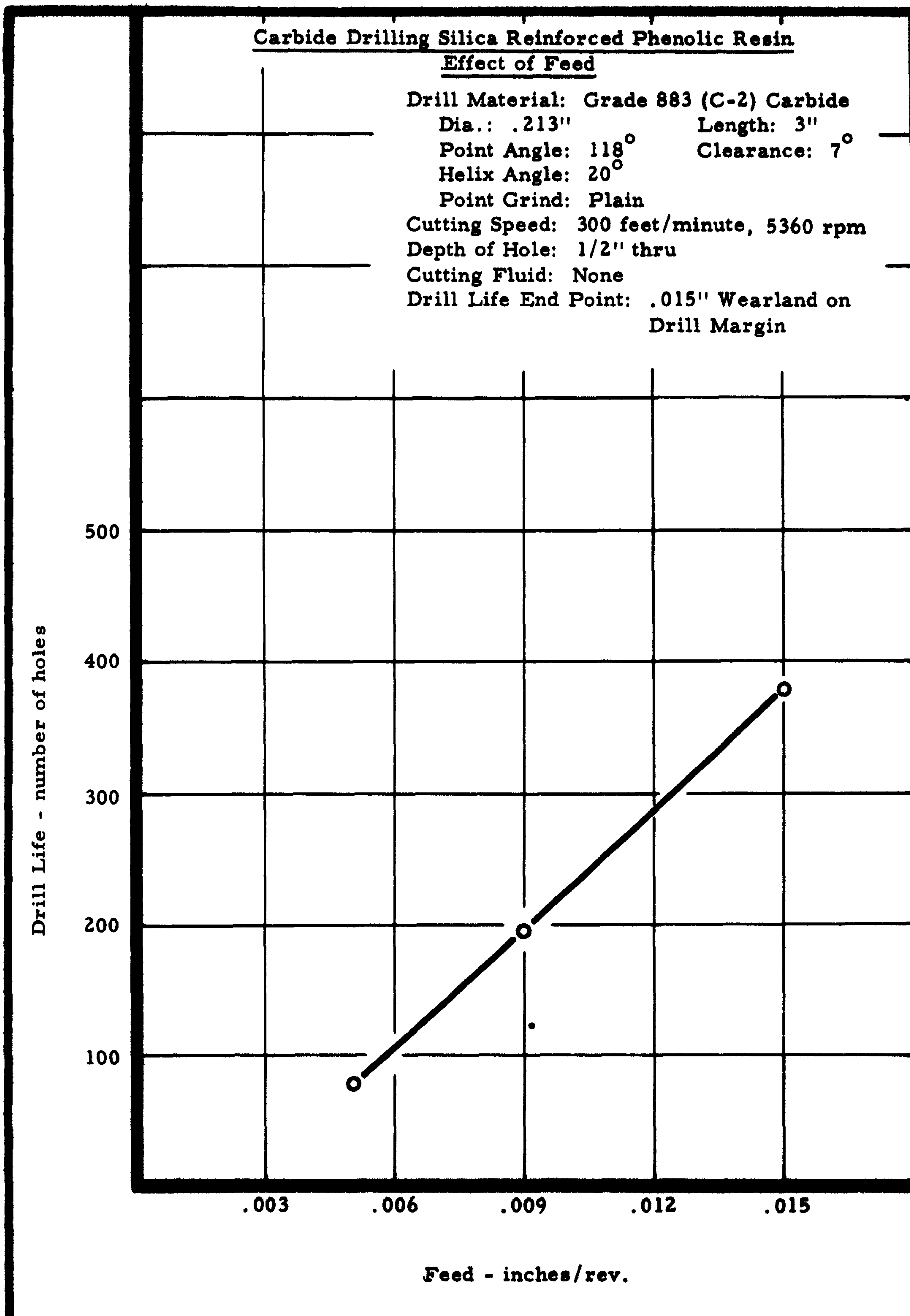
See Text page 23

Figure 38



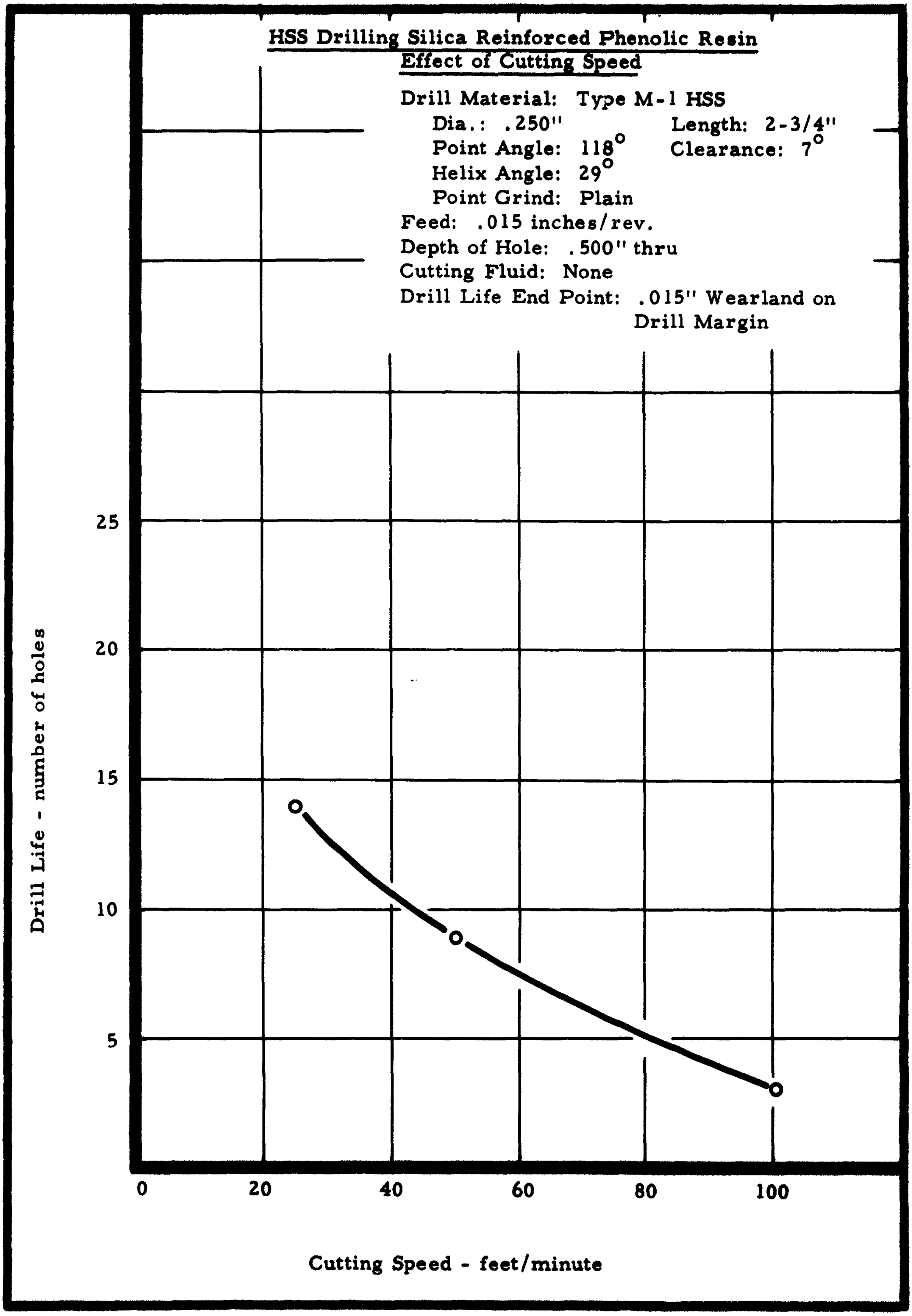
See Text page 23

Figure 39



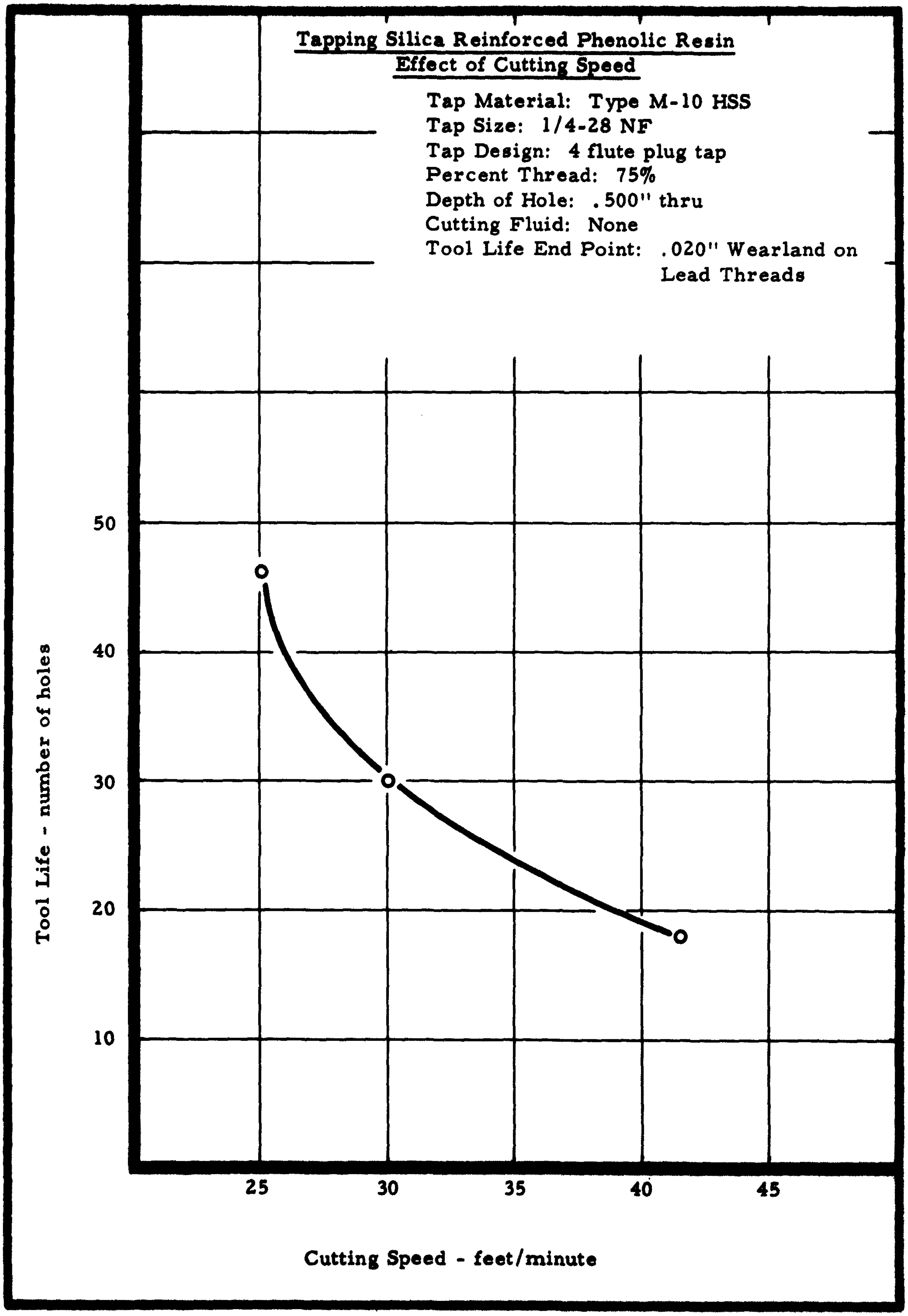
See Text page 24

Figure 40



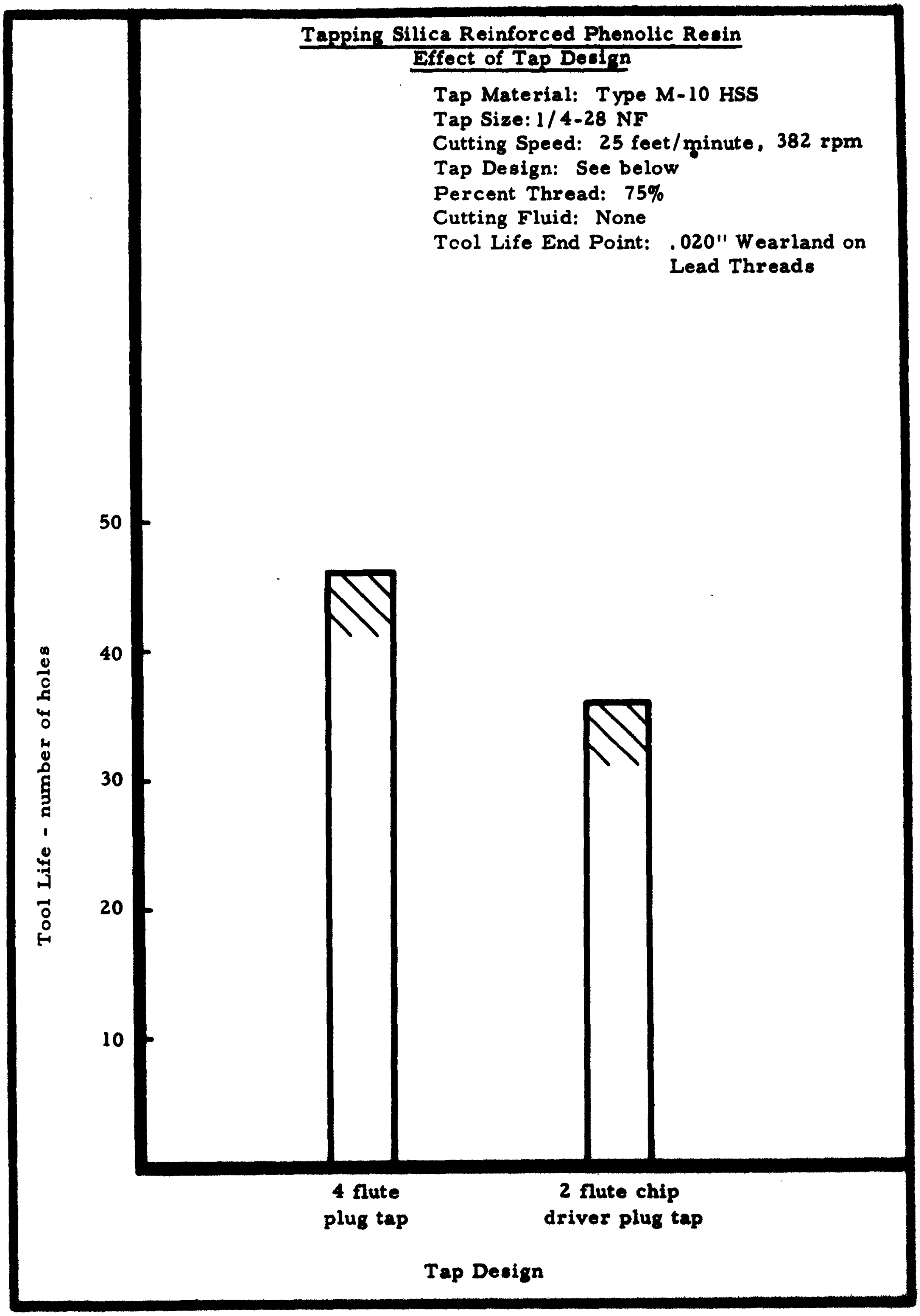
See Text page 24

Figure 41



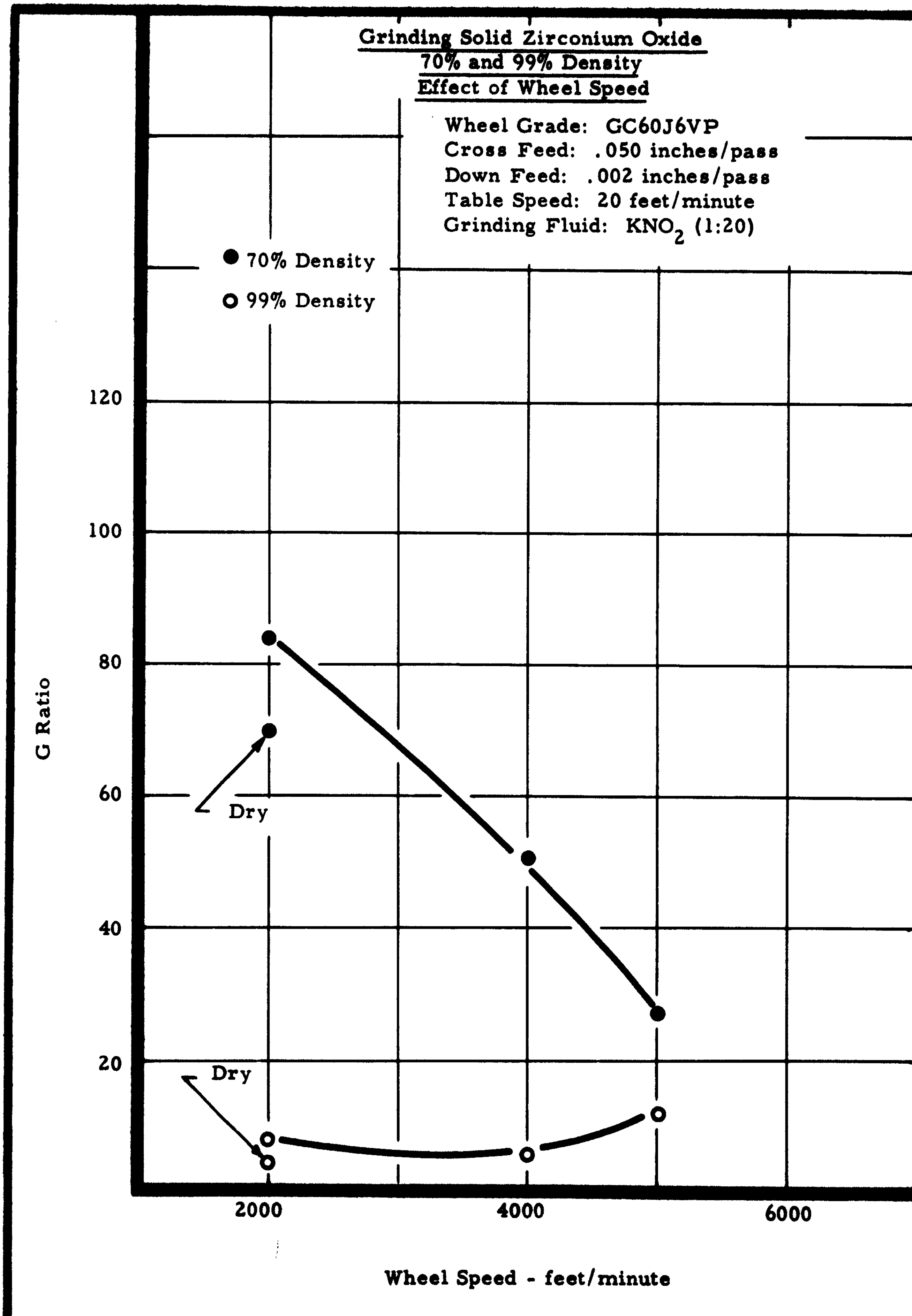
See Text page 24

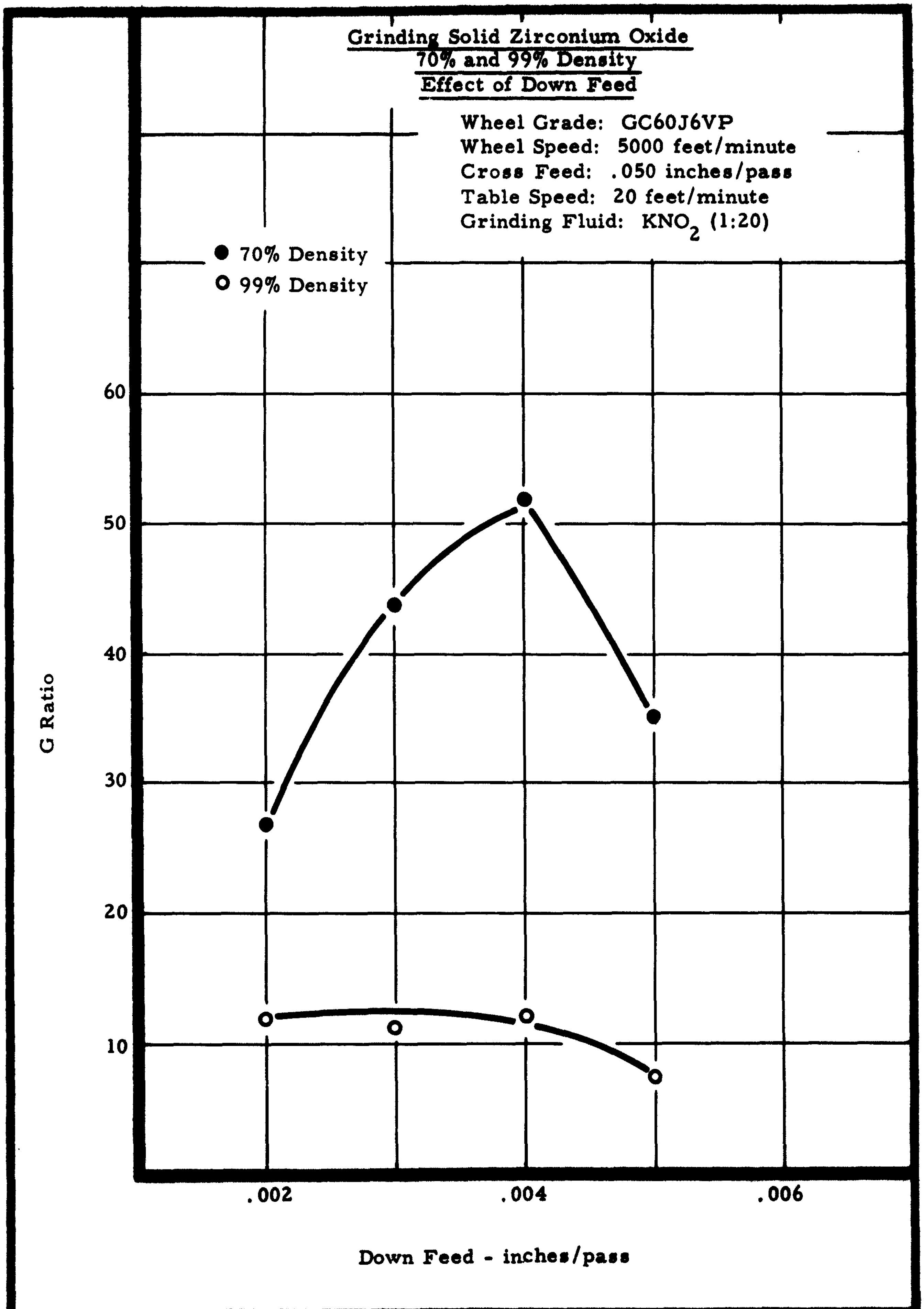
Figure 42



See Text page 24

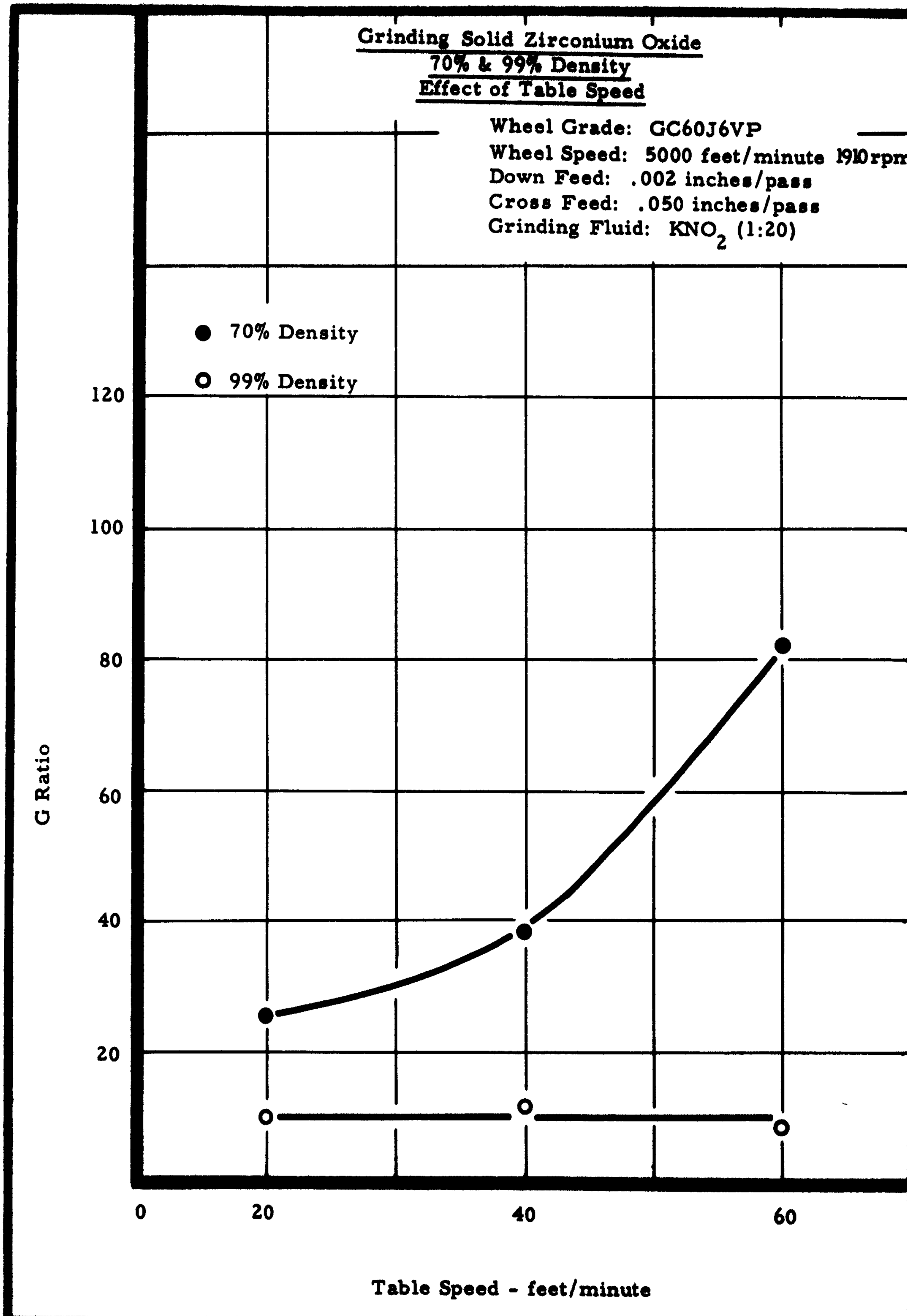
Figure 43

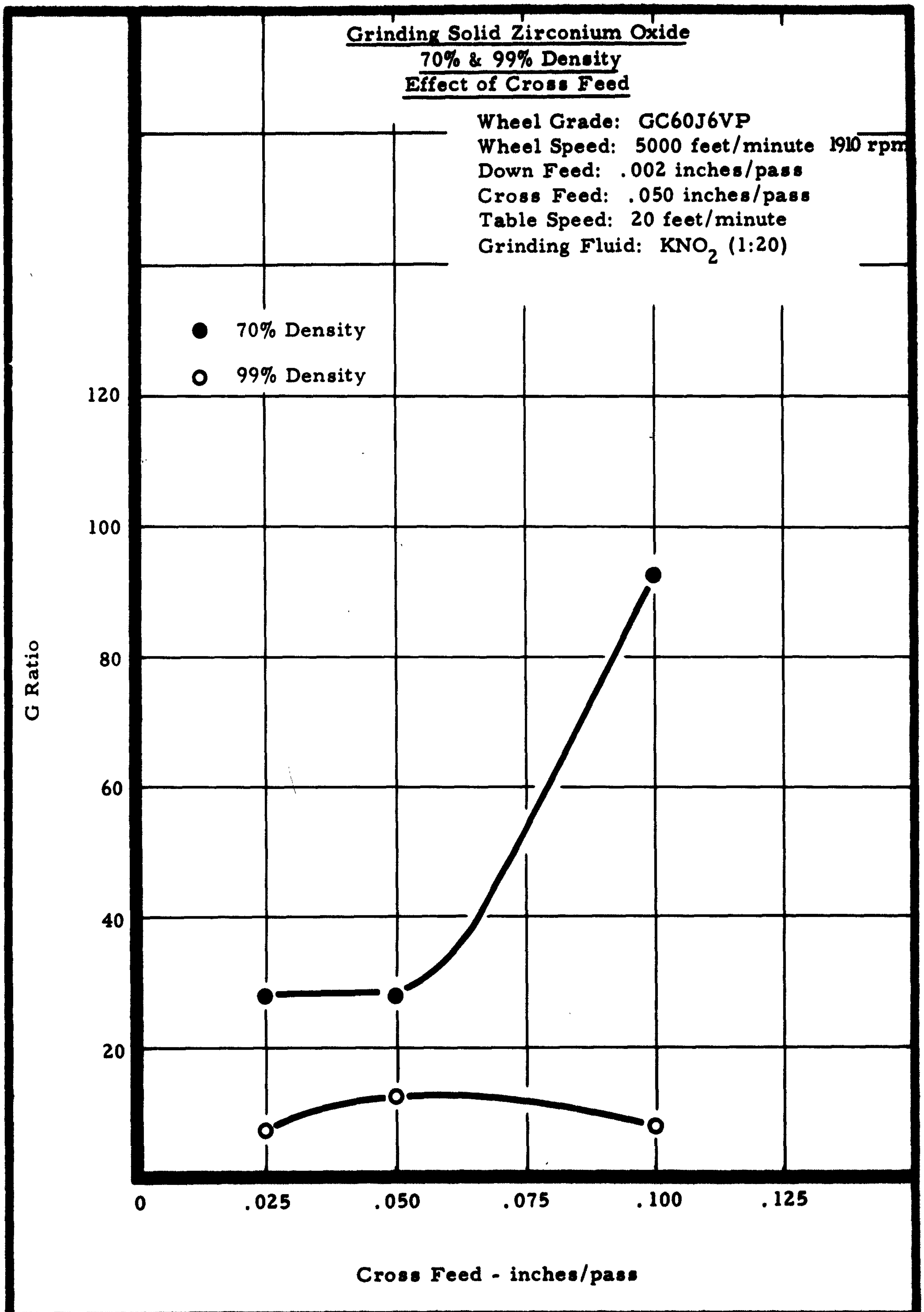

Grinding Solid Zirconium Oxide
70% and 99% Density
Effect of Wheel Speed
Wheel Grade: GC60J6VP
Cross Feed: .050 inches/pass
Down Feed: .002 inches/pass
Table Speed: 20 feet/minute
Grinding Fluid: KNO_2 (1:20)
70% Density
99% Density
Dry
Dry
G Ratio
120
100
80
60
40
20
2000
4000
6000
Wheel Speed - feet/minute



See Text page 25

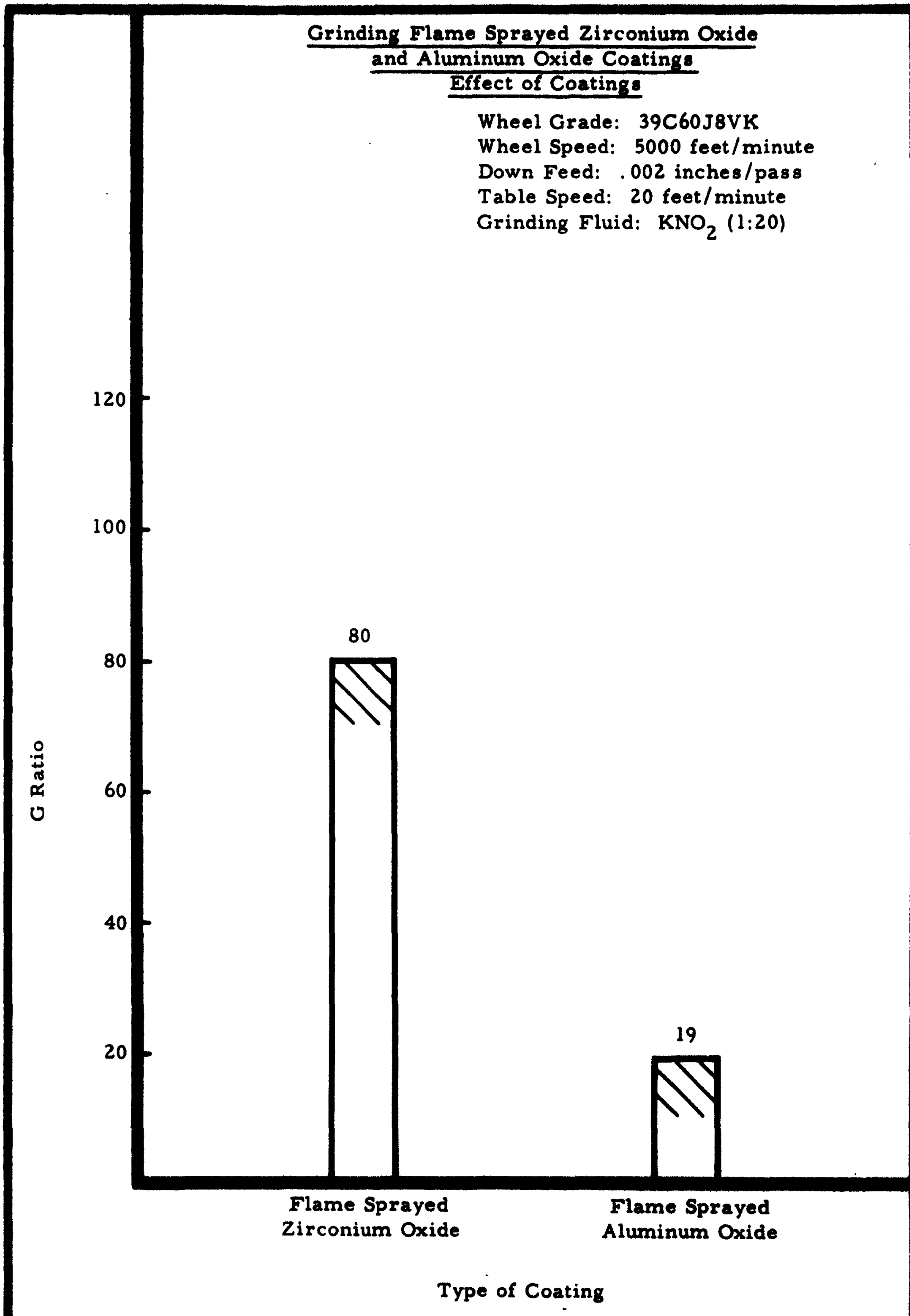
Figure 45


Grinding Solid Zirconium Oxide
70% & 99% Density
Effect of Table Speed
Wheel Grade: GC60J6VP
Wheel Speed: 5000 feet/minute 1910 rpm
Down Feed: .002 inches/pass
Cross Feed: .050 inches/pass
Grinding Fluid: KNO2 (1:20)
70% Density
99% Density
G Ratio
120
100
80
60
40
20
0
20
40
60
Table Speed - feet/minute



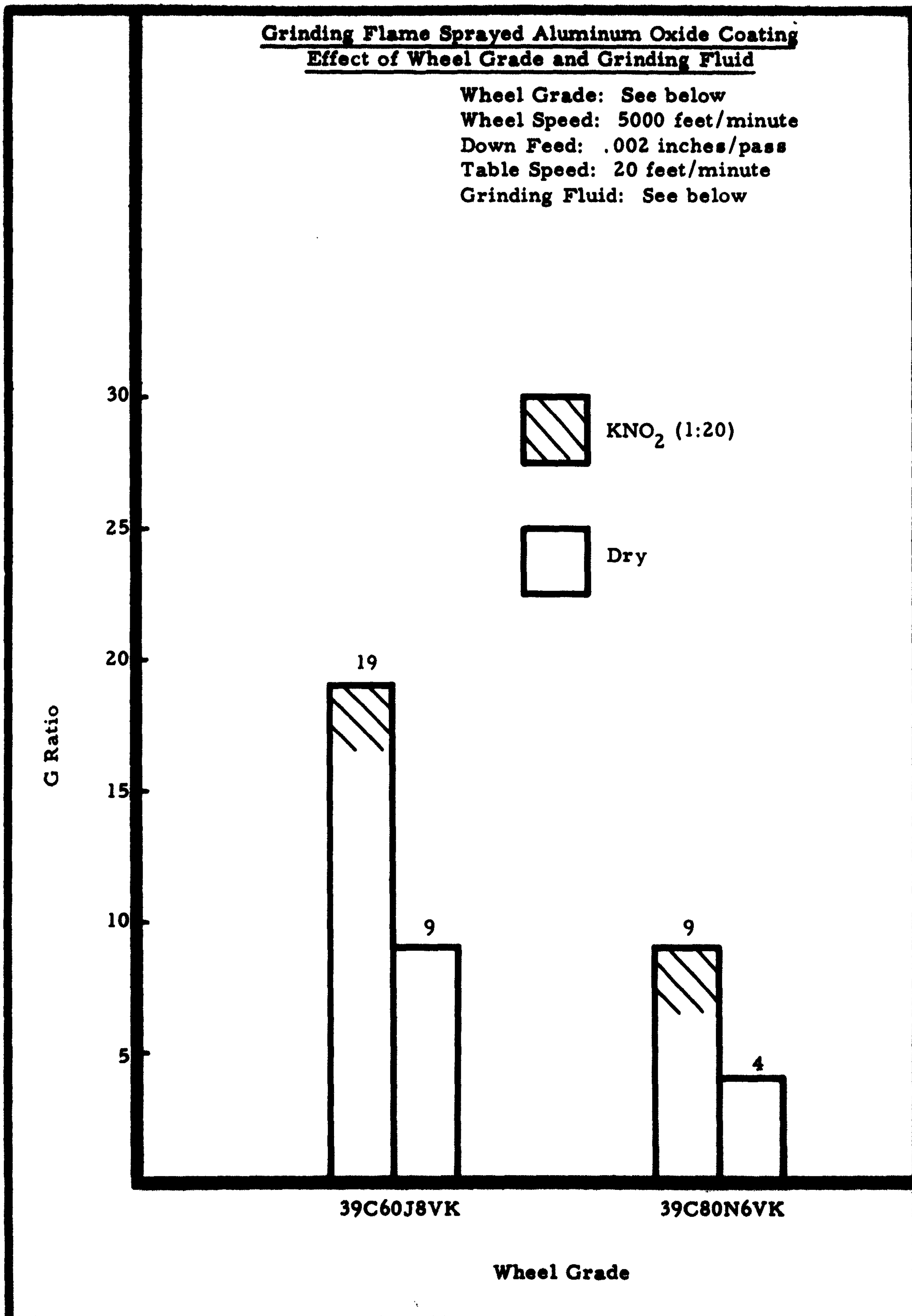
See Text page 26

Figure 47



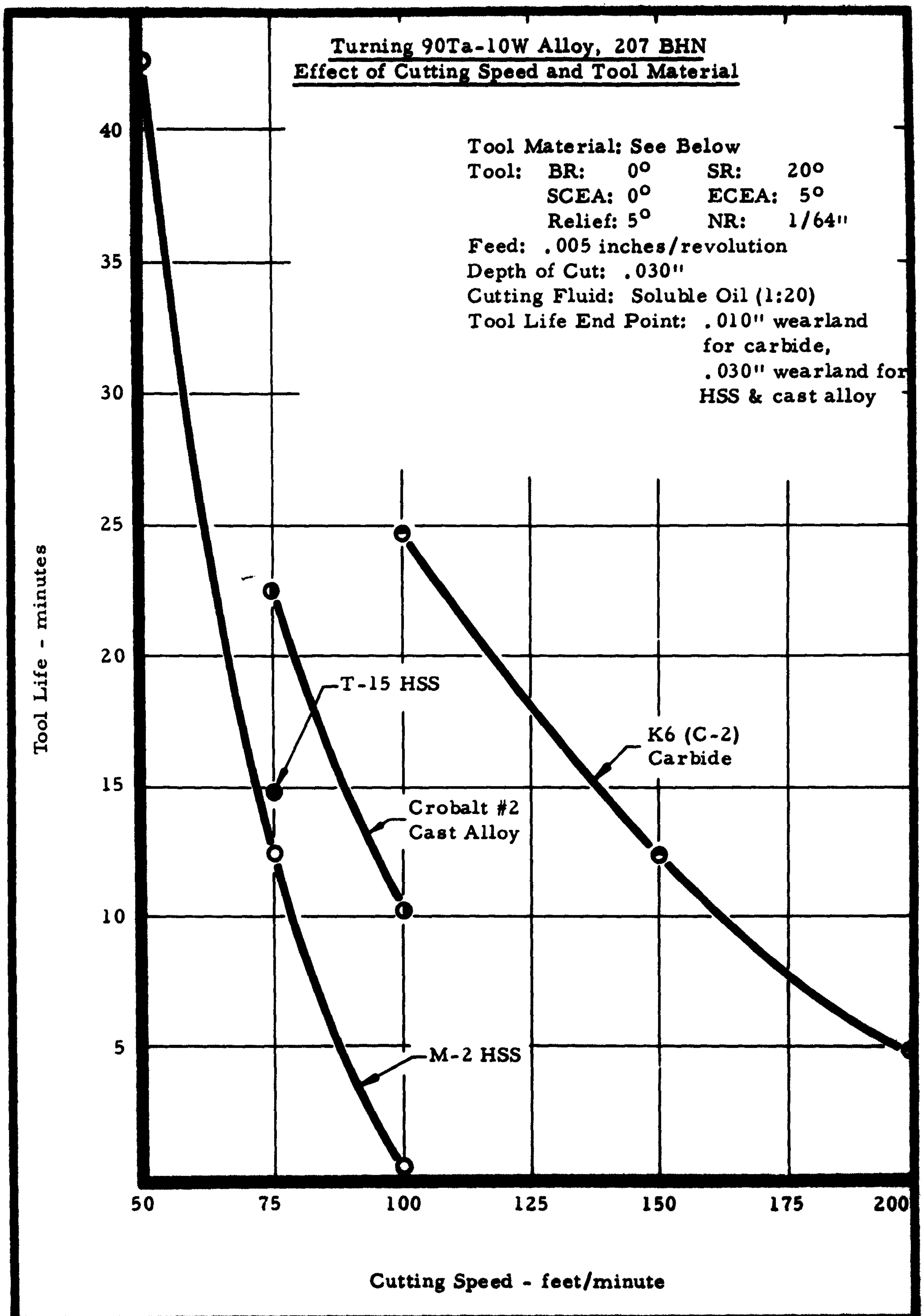
See Text page 26

Figure 48



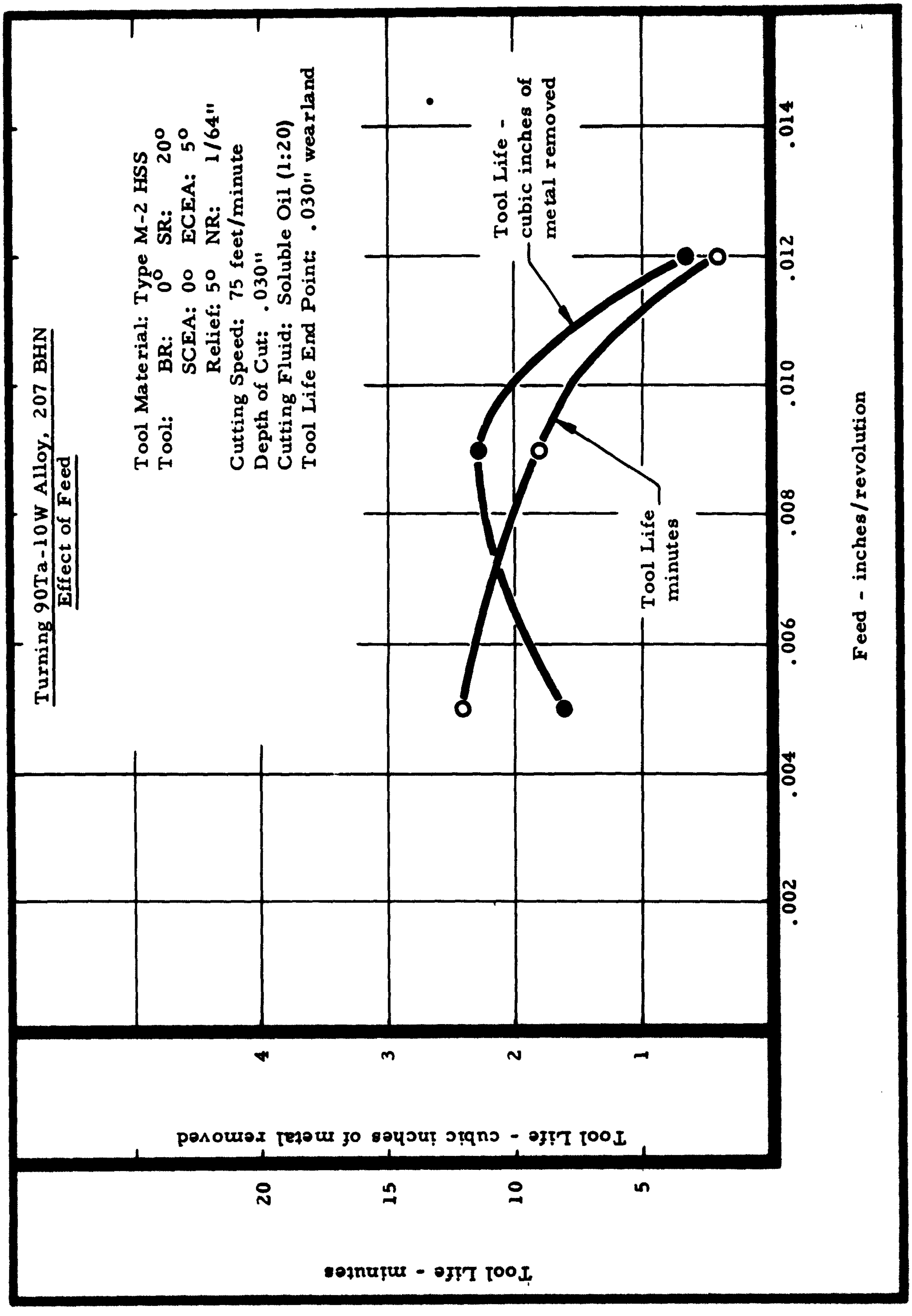
See Text page 26

Figure 49



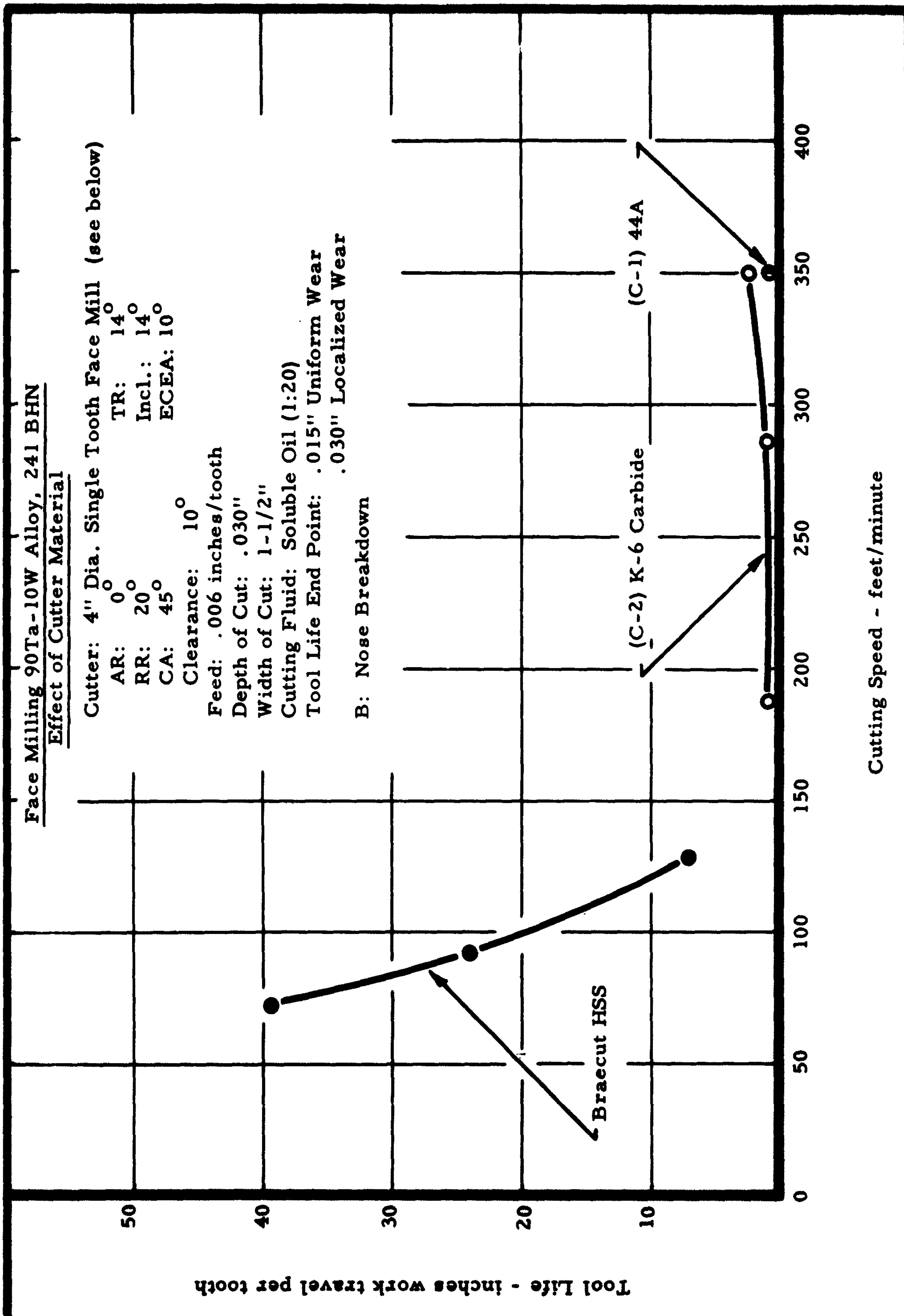
See text, page 27

Figure 50

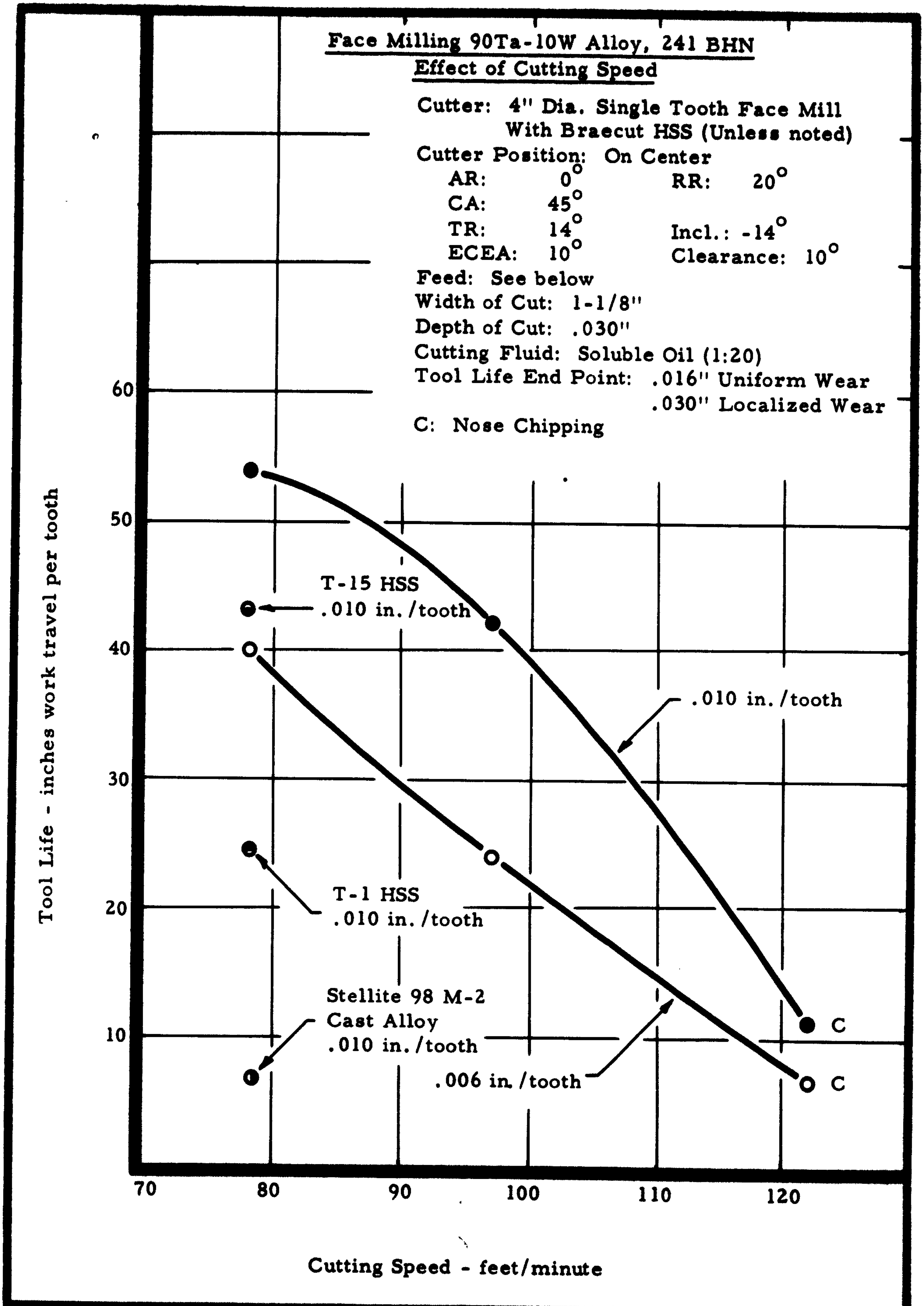


See text, page 27

Figure 51

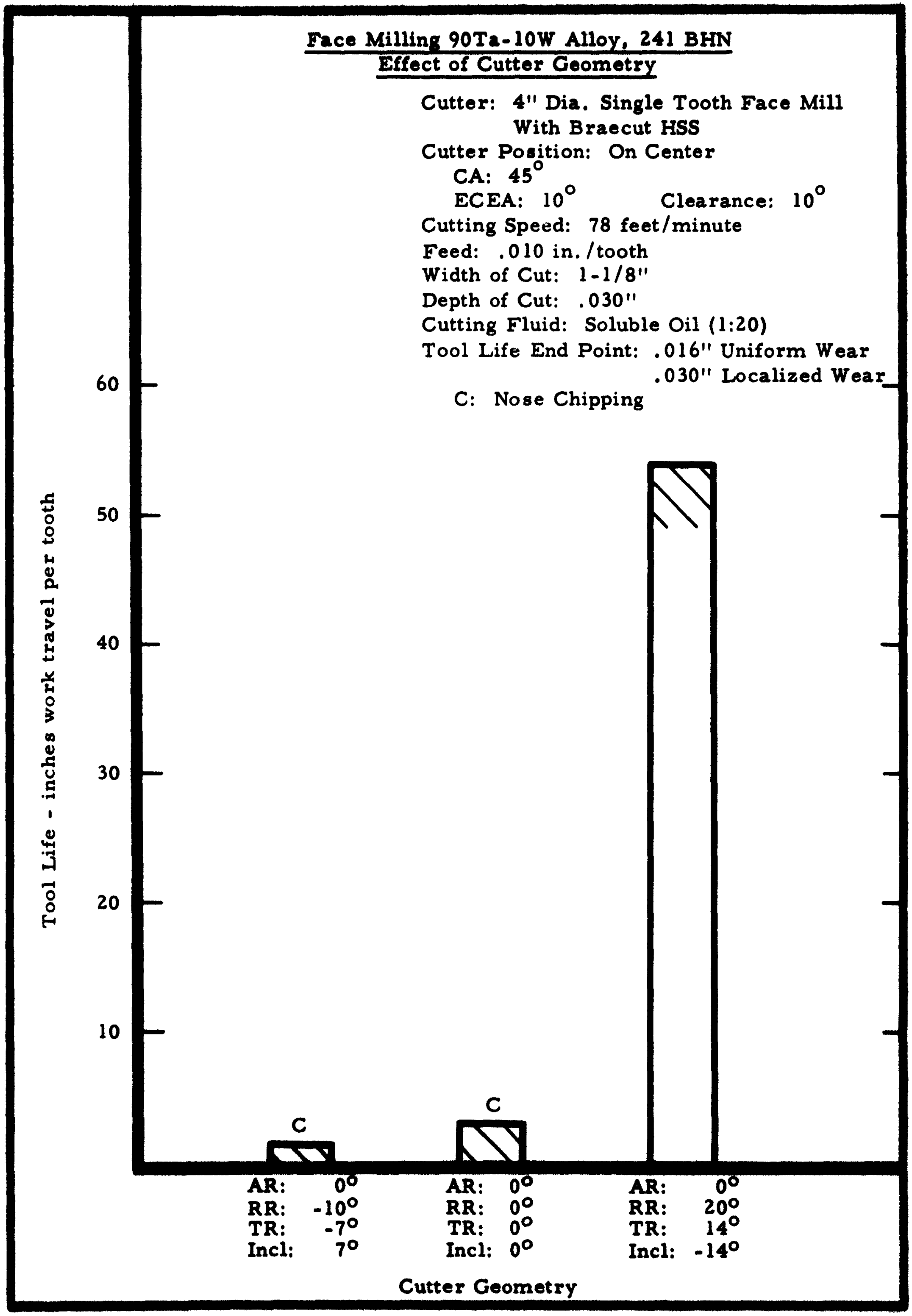


See Text page 27 Figure 52



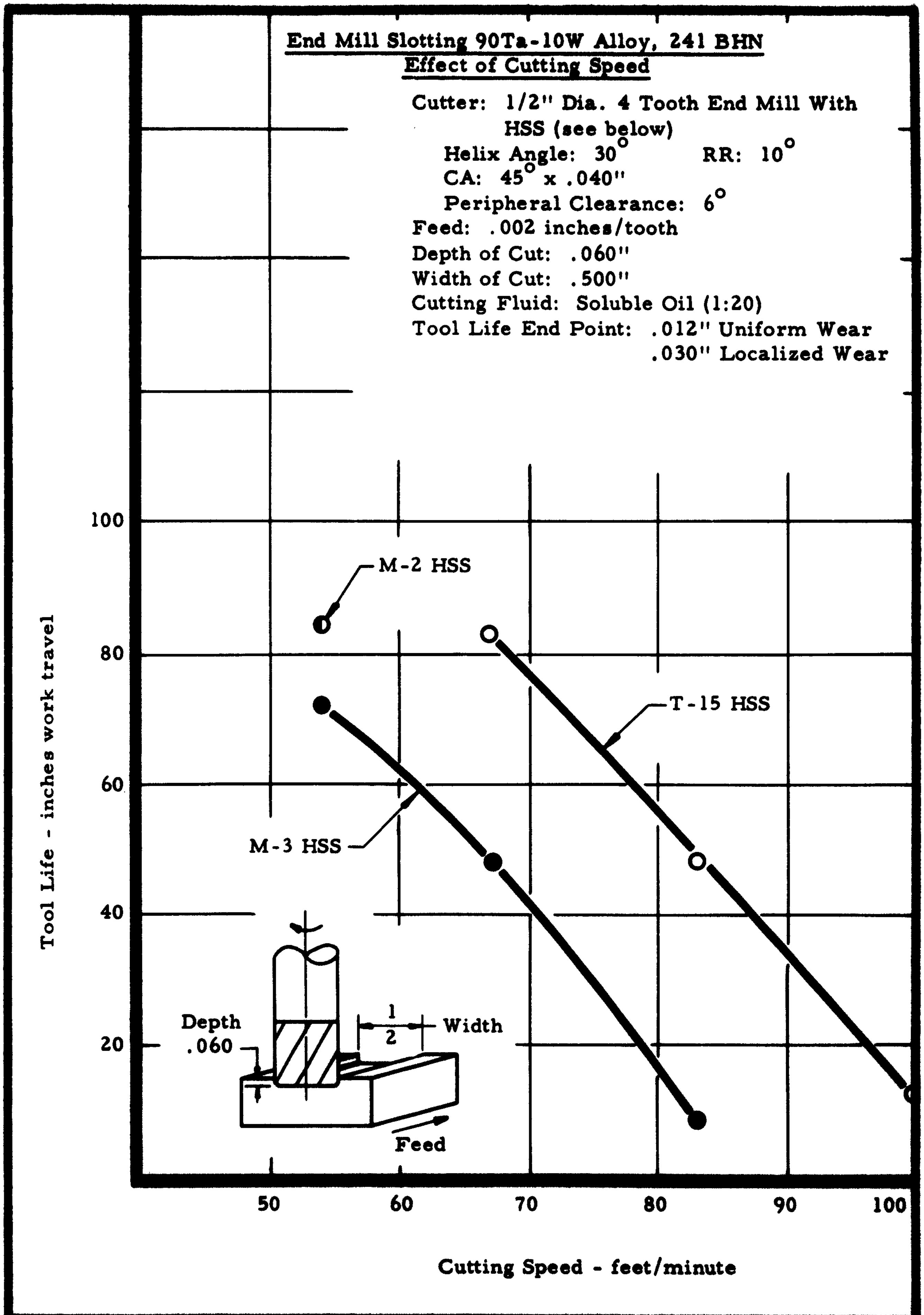
See Text page 27

Figure 53



See text, page 28

Figure 54


End Mill Slotting 90Ta-10W Alloy, 241 BHN
Effect of Cutting Speed
Cutter: 1/2" Dia. 4 Tooth End Mill With HSS (see below)
Helix Angle: 30° RR: 10°
CA: 45° x .040"
Peripheral Clearance: 6°
Feed: .002 inches/tooth
Depth of Cut: .060"
Width of Cut: .500"
Cutting Fluid: Soluble Oil (1:20)
Tool Life End Point: .012" Uniform Wear
.030" Localized Wear
M-2 HSS
T-15 HSS
M-3 HSS
Depth
.060
1/2
Width
Feed
Tool Life - inches work travel
100
80
60
40
20
50
60
70
80
90
100
Cutting Speed - feet/minute

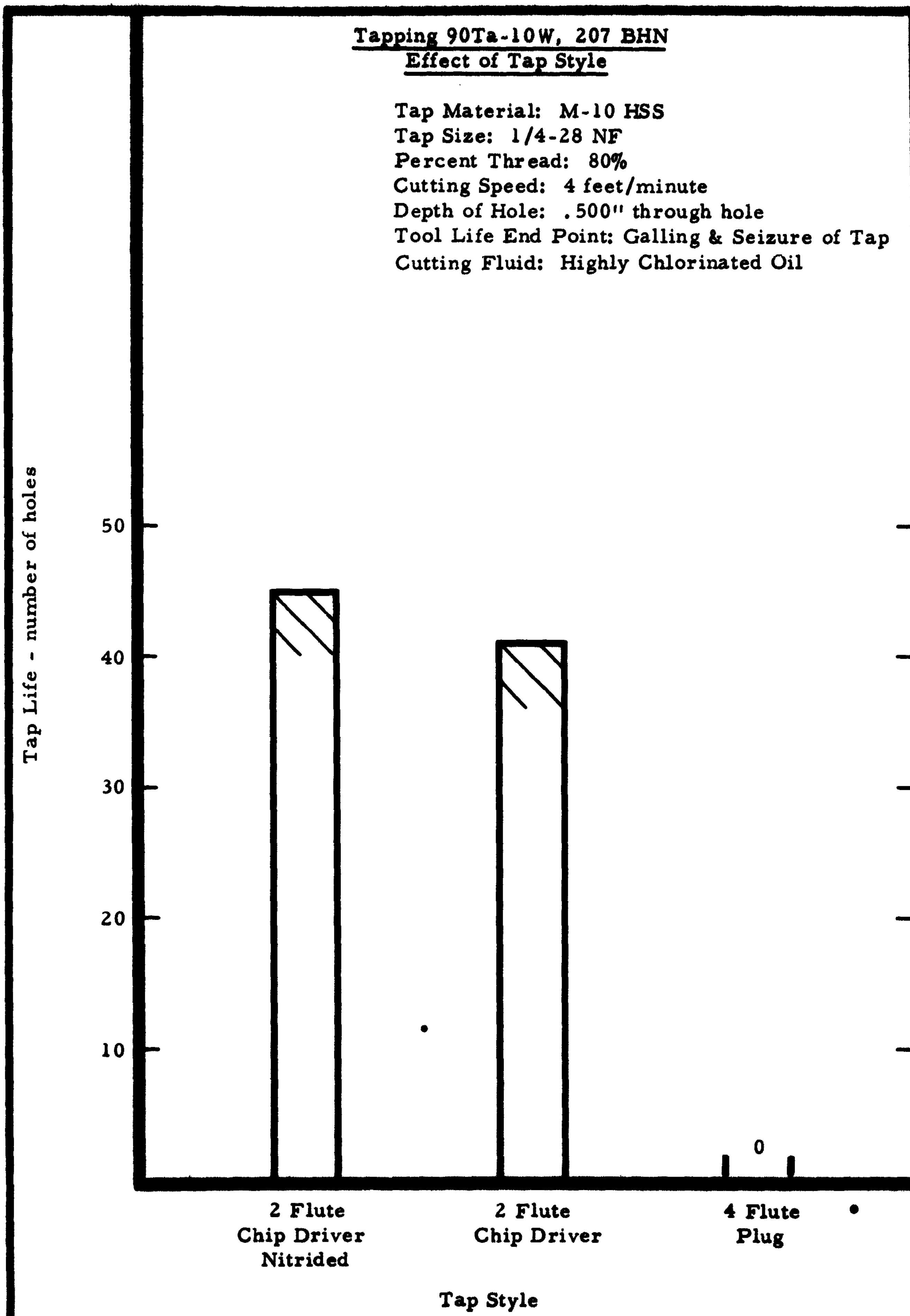


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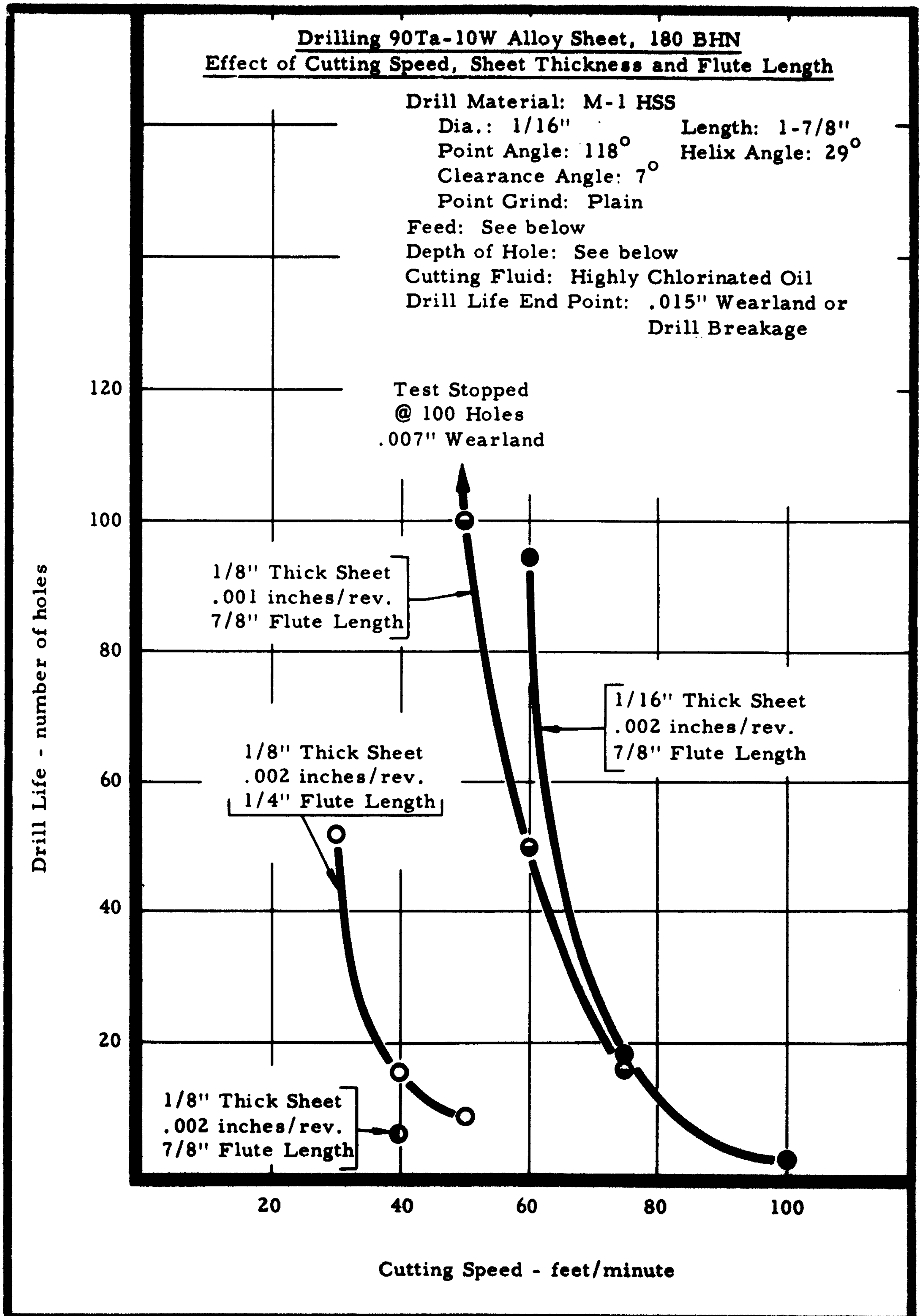
Figure 56



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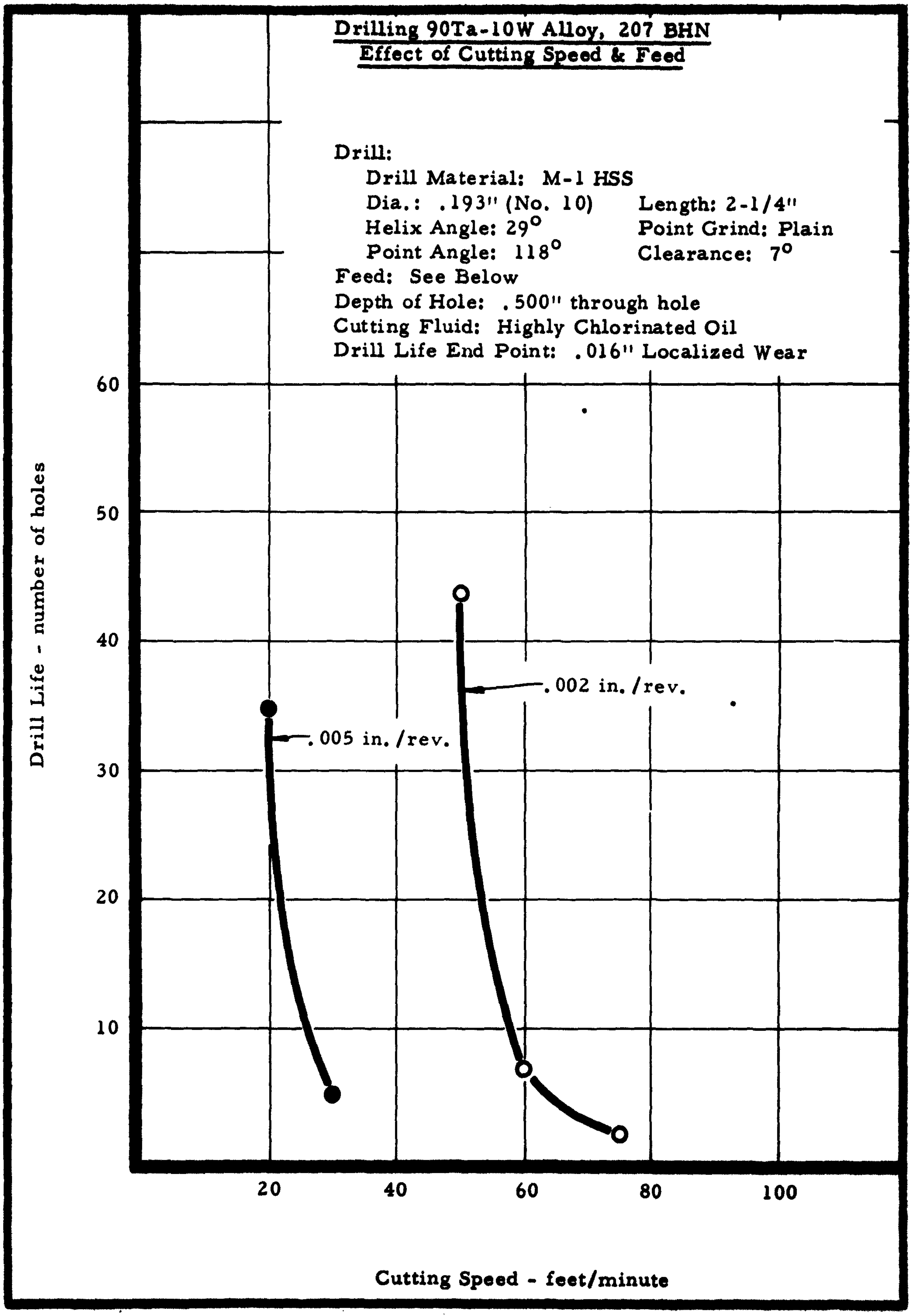
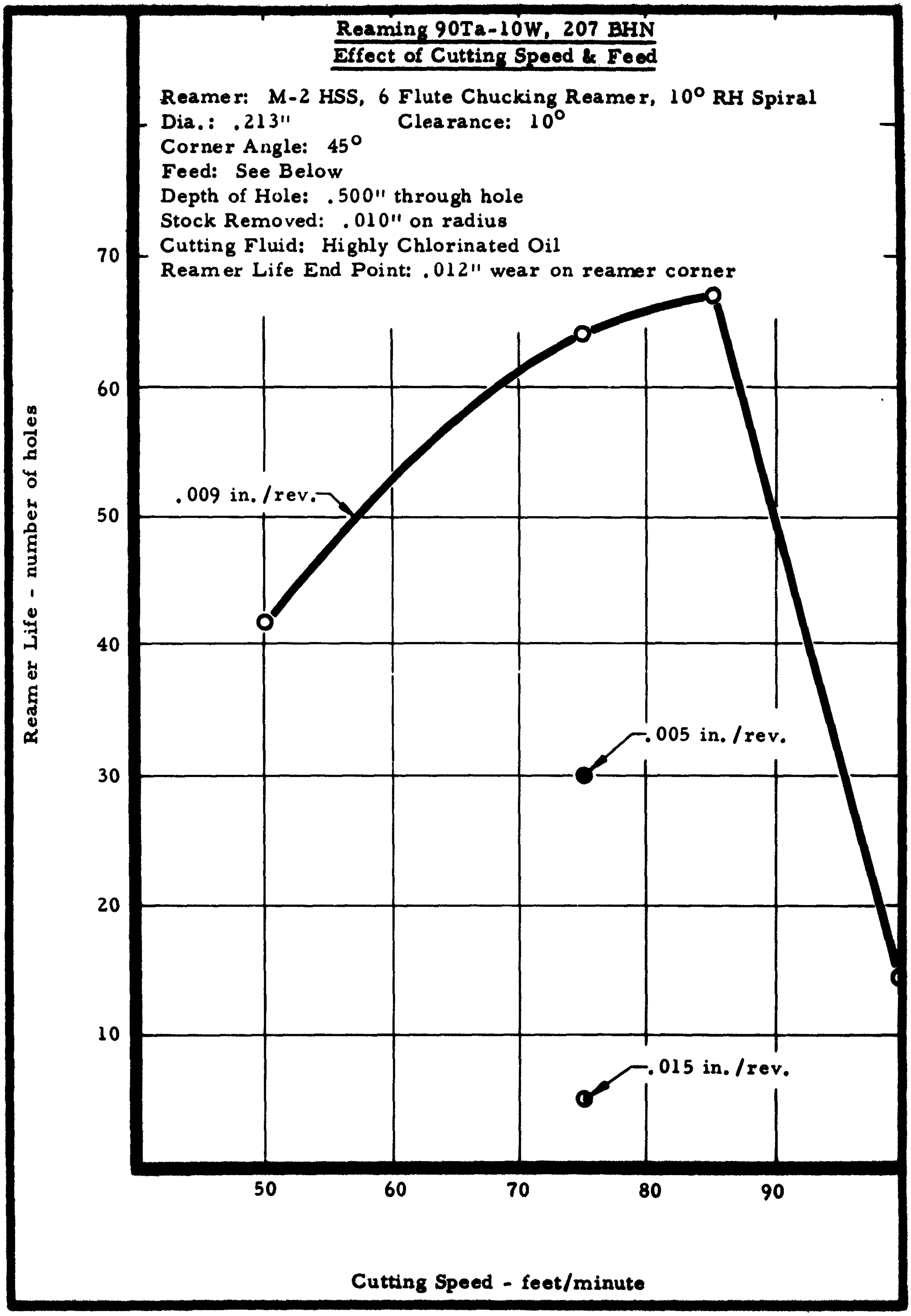


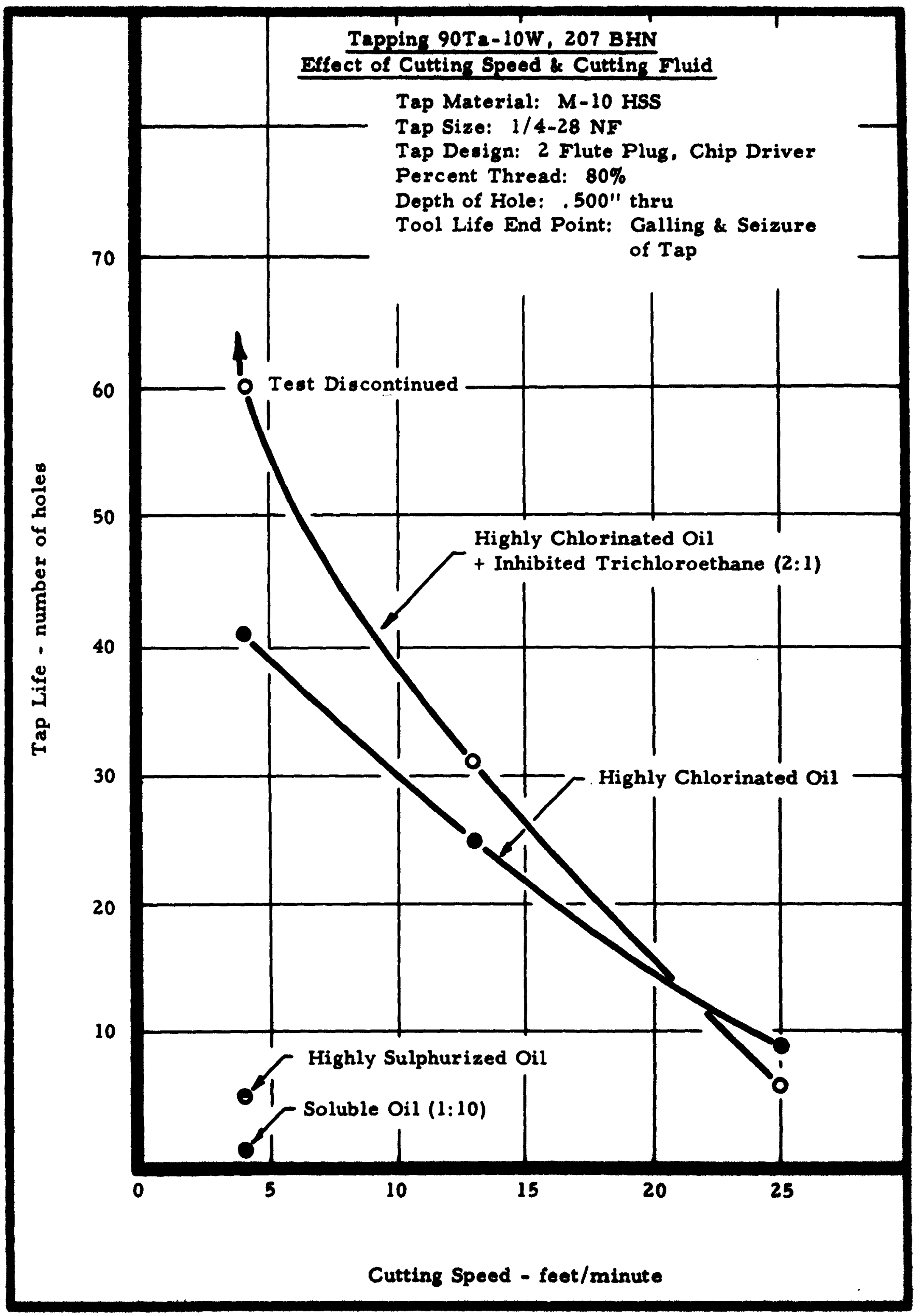
See text, page 28

Figure 58



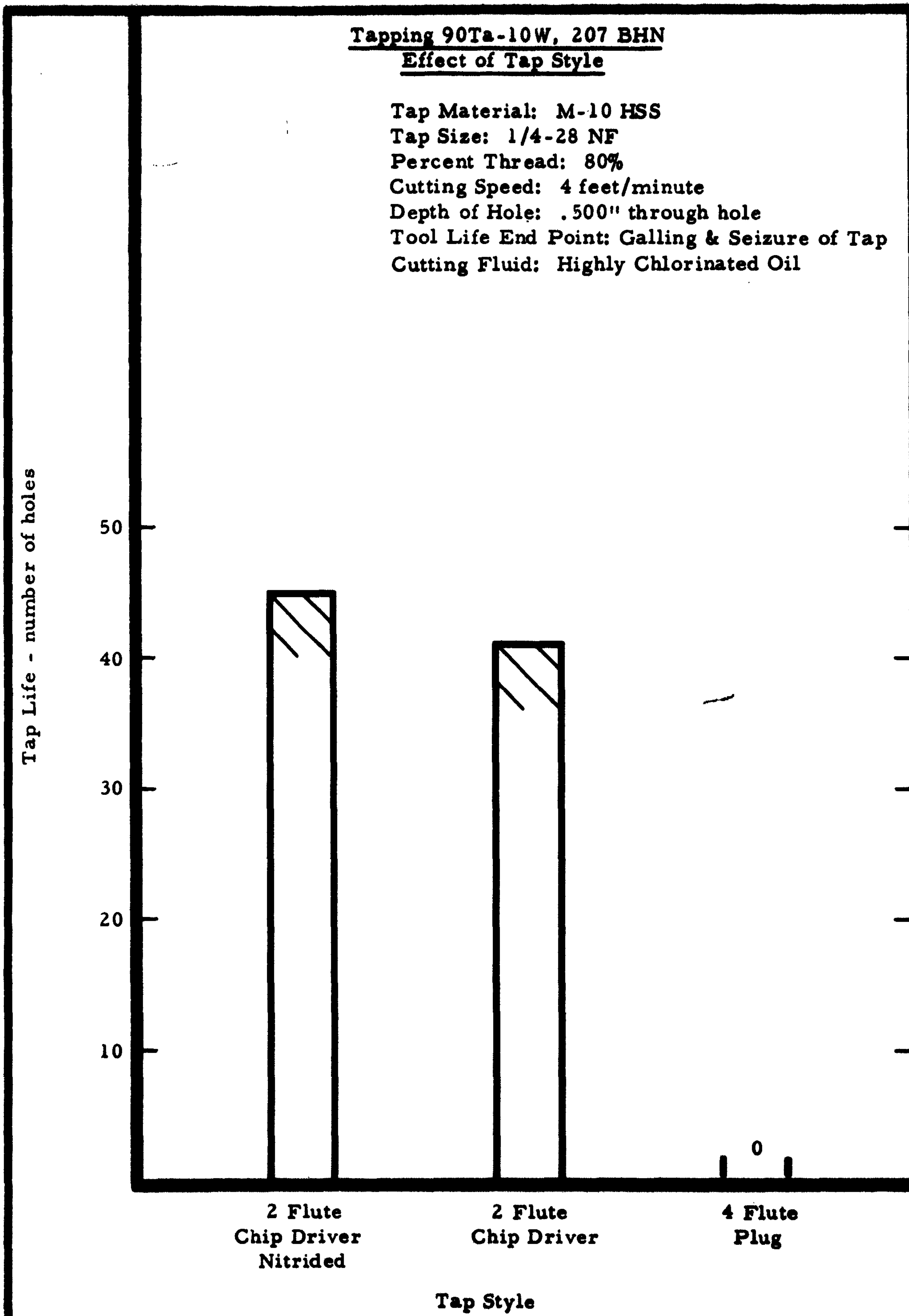
See text, page 29

Figure 59



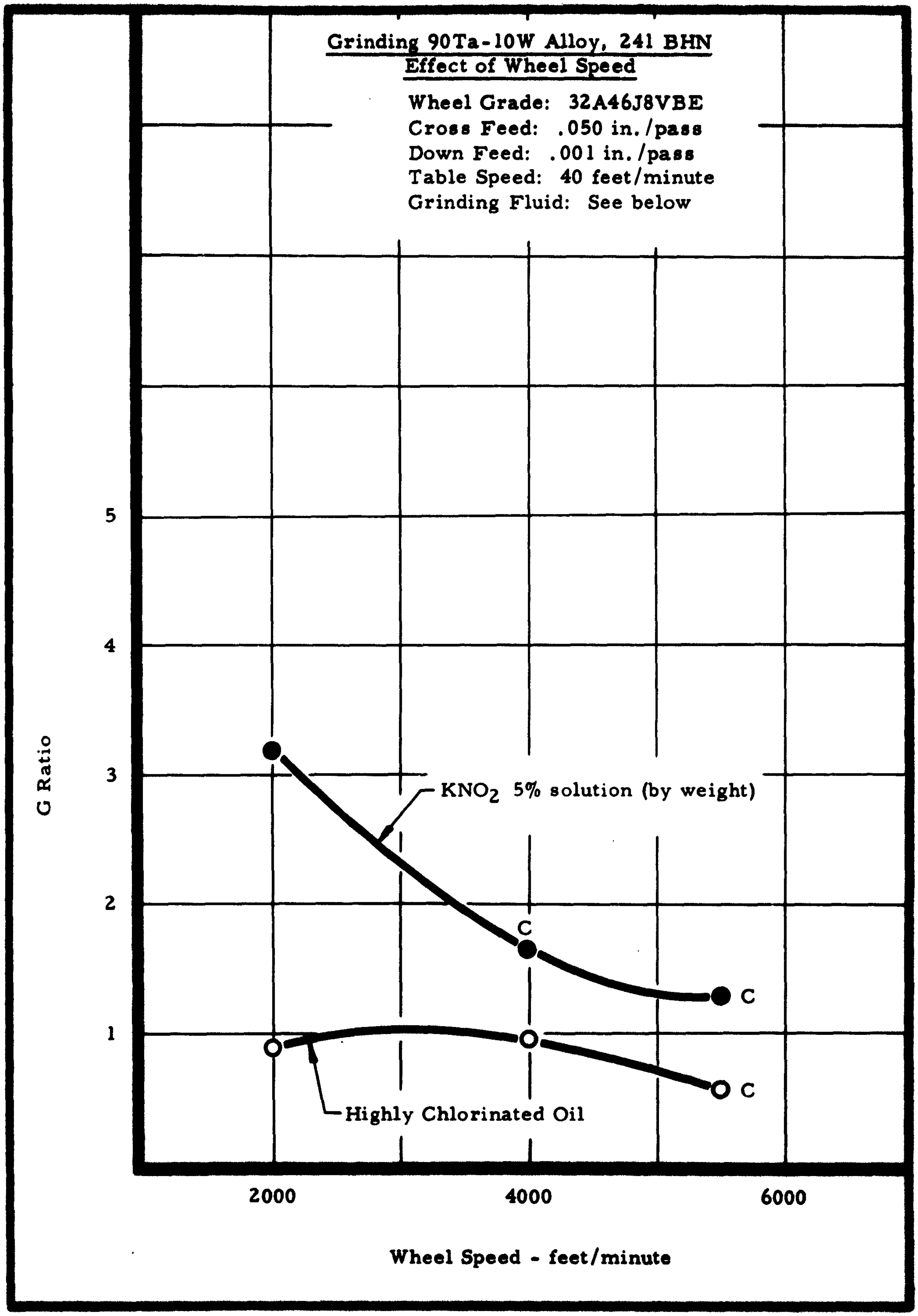
See Text page 29

Figure 60



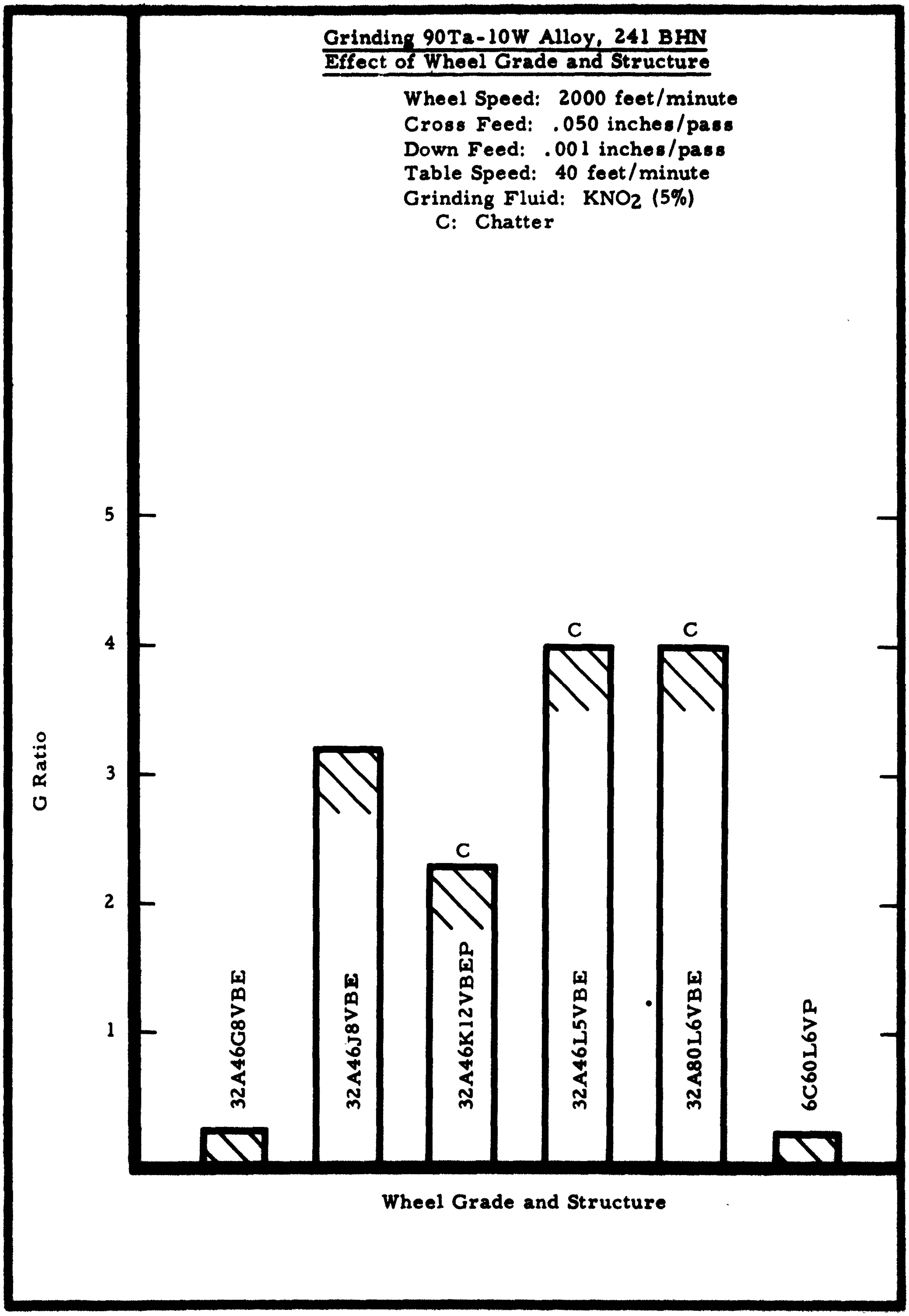
See text, page 29

Figure 61



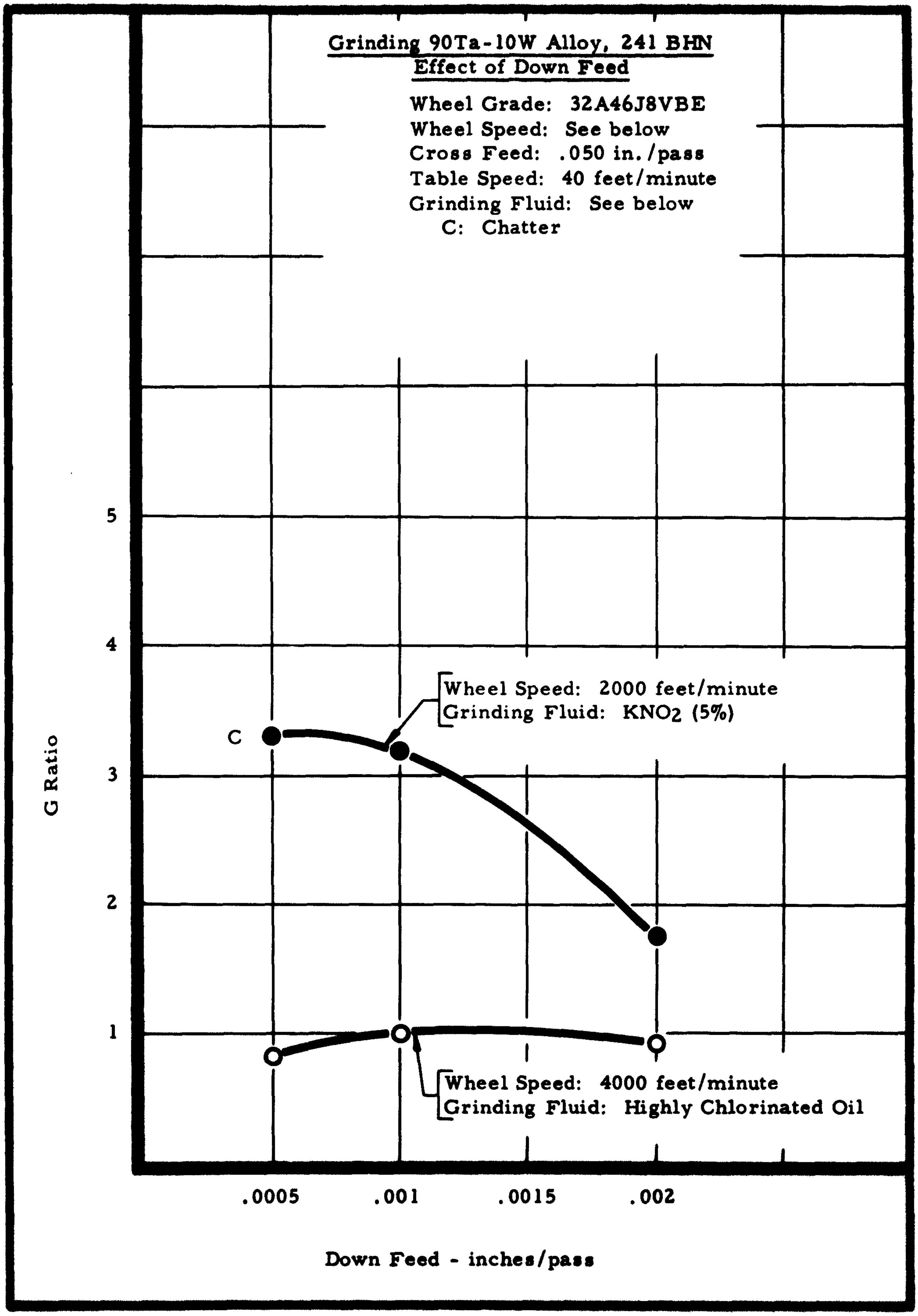
See text, page 29

Figure 62



See text, page 29

Figure 63



See text, page 29

Figure 64

TABLE 1.

RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING
90Ta-10W ALLOY, 207-241 BHN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min.	Tool Life	Wear-land inches	Cutting Fluid
Turning	M-2 HSS	BR: 0° SCEA: 0° SR: 20° ECEA: 5° Relief: 5° NR: 1/64"	5/8" square solid HSS	.030	-	.009 in/rev	50	44 min.	.030	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 0° SCEA: 0° SR: 20° ECEA: 5° Relief: 5° NR: 1/64"	5/8" square brazed tool bit	.030	-	.009 in/rev	75	27 min.	.010	Soluble Oil (1:20)
Face Milling	Super HSS	AR: 0° ECEA: 10° RR: 20° CA: 45° Clearance: 10°	4" diameter single tooth face mill	.030	1.125	.010 in/tooth	80	53 in/tooth	.016	Soluble Oil (1:20)
End Mill Slotting	T-15 HSS	Helix Angle: 30° RR: 10° Clearance: 15° CA: 45° x .040"	1/2" diameter 4 tooth HSS end mill	.060	.500	.002 in/tooth	70	80 inches	.012	Soluble Oil (1:20)
End Mill Peripheral Cut	M-2 HSS	Helix Angle: 30° RR: 10° Clearance: 6° CA: 45° x .040"	1/2" diameter 4 tooth HSS end mill	.060	.500	.002 in/tooth	65	70 inches	.012	Soluble Oil (1:20)
Drilling	M-1 HSS	118° plain point 7° clearance angle	.125" diameter drill 2-3/4" long	1/8" thru hole	-	.002 in/rev	50	125 holes	.015	Highly Chlorinated Oil

TABLE 1 (continued)

RECOMMENDED CONDITIONS FOR MACHINING AND GRINDING

90Ta-10W ALLOY, 207-241 BHN

Operation	Tool Material	Tool Geometry	Tool Used for Tests	Depth of Cut inches	Width of Cut inches	Feed	Cutting Speed ft./min	Tool Life	Wear-land inches	Cutting Fluid
Reaming	M-2 HSS	10° RH Helix CA: 45° Clearance: 10°	.213" diameter 6 flute straight shank chucking reamer	1/2" thru hole	.010" depth on hole radius	.009 in/rev	85	66	.012	Highly Chlorinated Oil
Tapping	M-10 HSS	2 flute chip driver tap 80% thread	1/4-28 NF tap	1/2" thru hole	-	-	4.5	60^{+} holes	-	Highly Chlorinated Oil + Inhibited Trichloroethane (2:1)

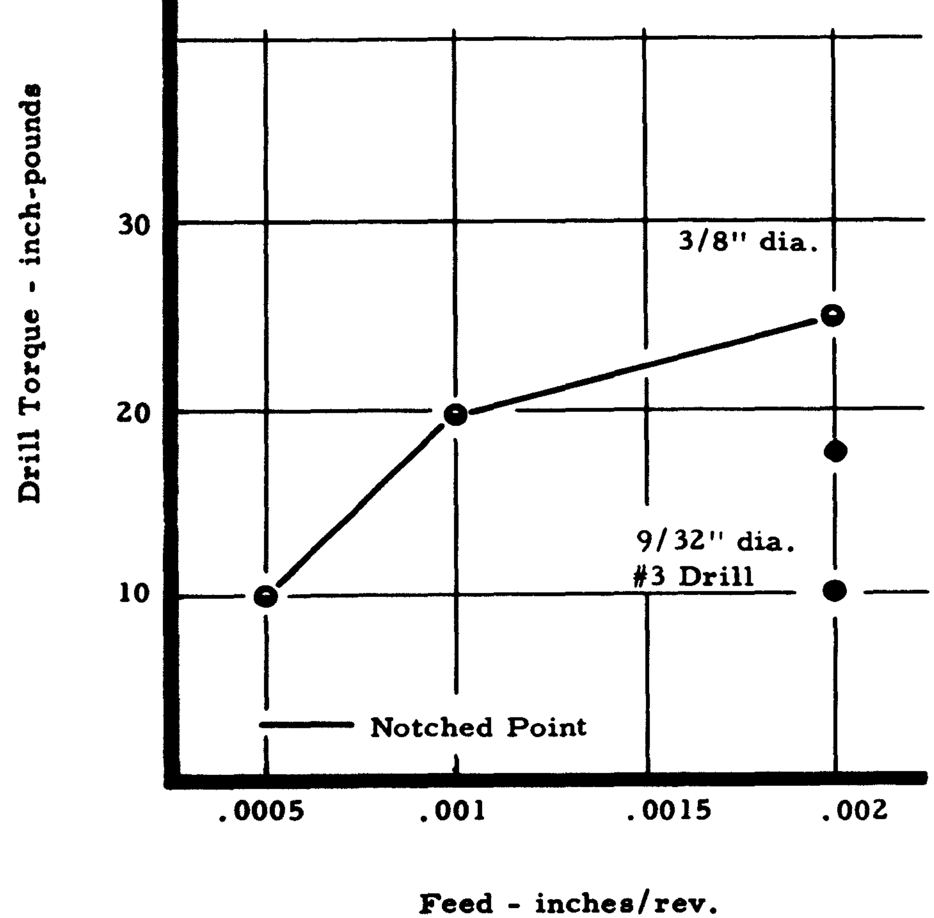
SURFACE GRINDING

Wheel Grade	Grinding Fluid	Wheel Speed feet/minute	Table Speed feet/minute	Down Feed inches/pass	Cross Feed inches/pass	G Ratio
32A46J8VBE	5%, KNO_2 Solution	2000*	20	.001	.025	4.5
32A46J8VBE	Highly Chlorinated Oil	4000	40	.002	.050	1

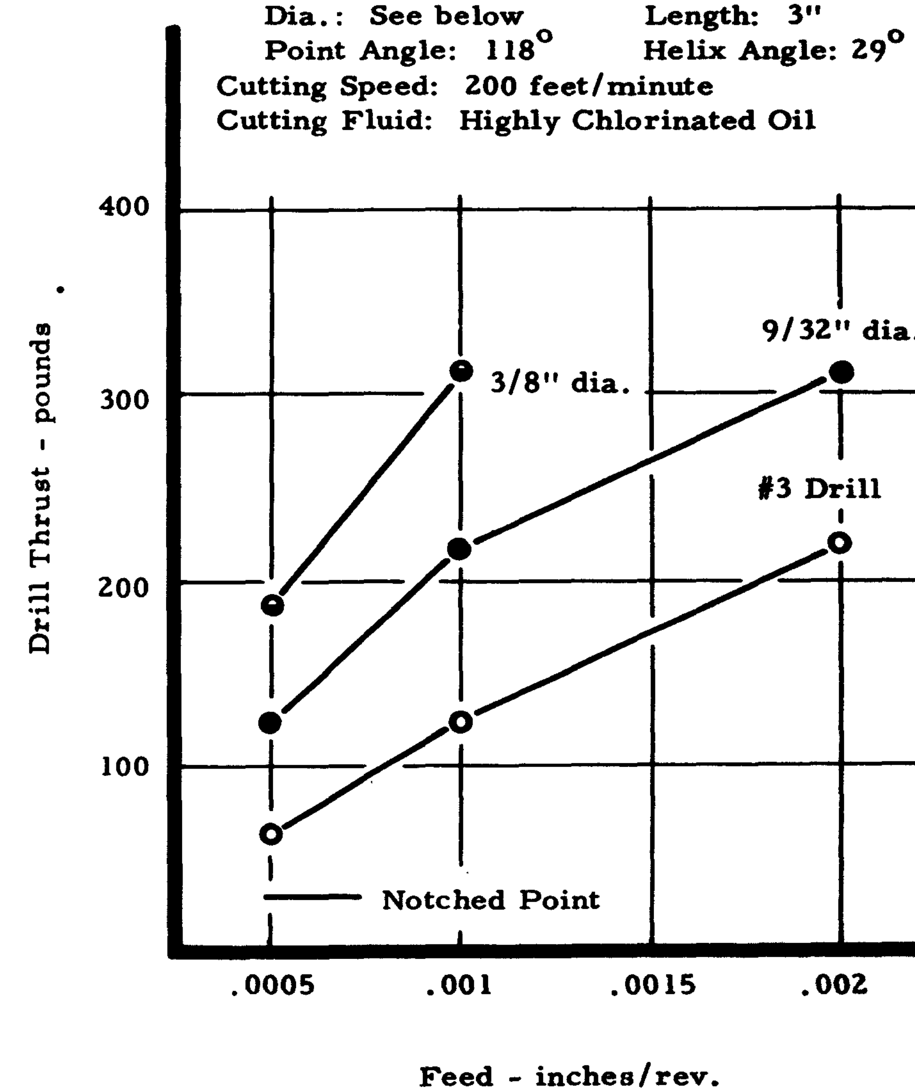
*If wheel speed of 2000 feet/minute is not available, use conditions for wheel speed of 4000 feet/minute.

Drilling Pressed and Sintered Tungsten
Drill Torque and Drill Thrust

Drill: Grade 883 (C-2) Carbide
Dia.: See below Length: 3"
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil

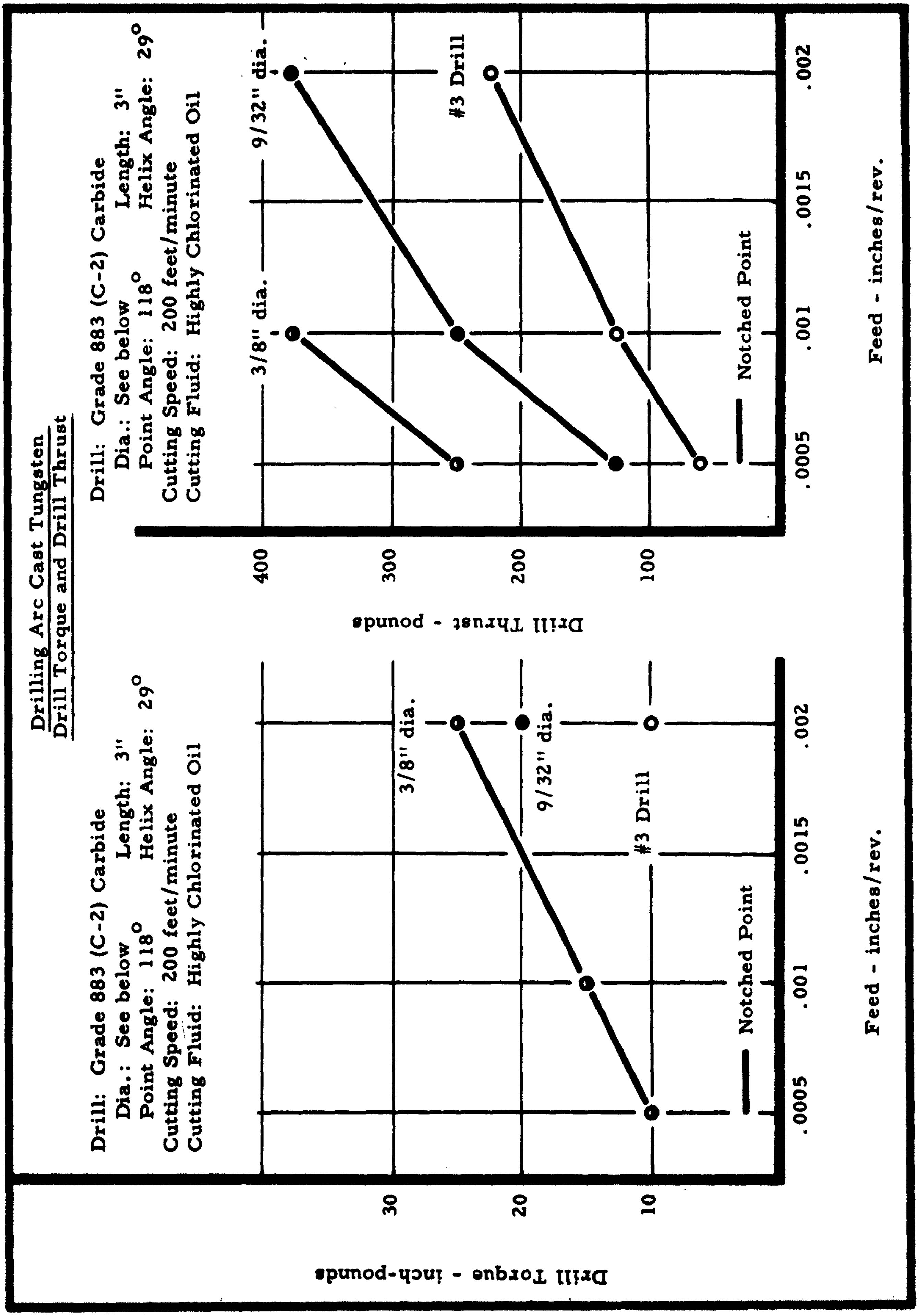


Drill: Grade 883 (C-2) Carbide
Dia.: See below Length: 3"
Point Angle: 118° Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil



See Text page 30

Figure 65

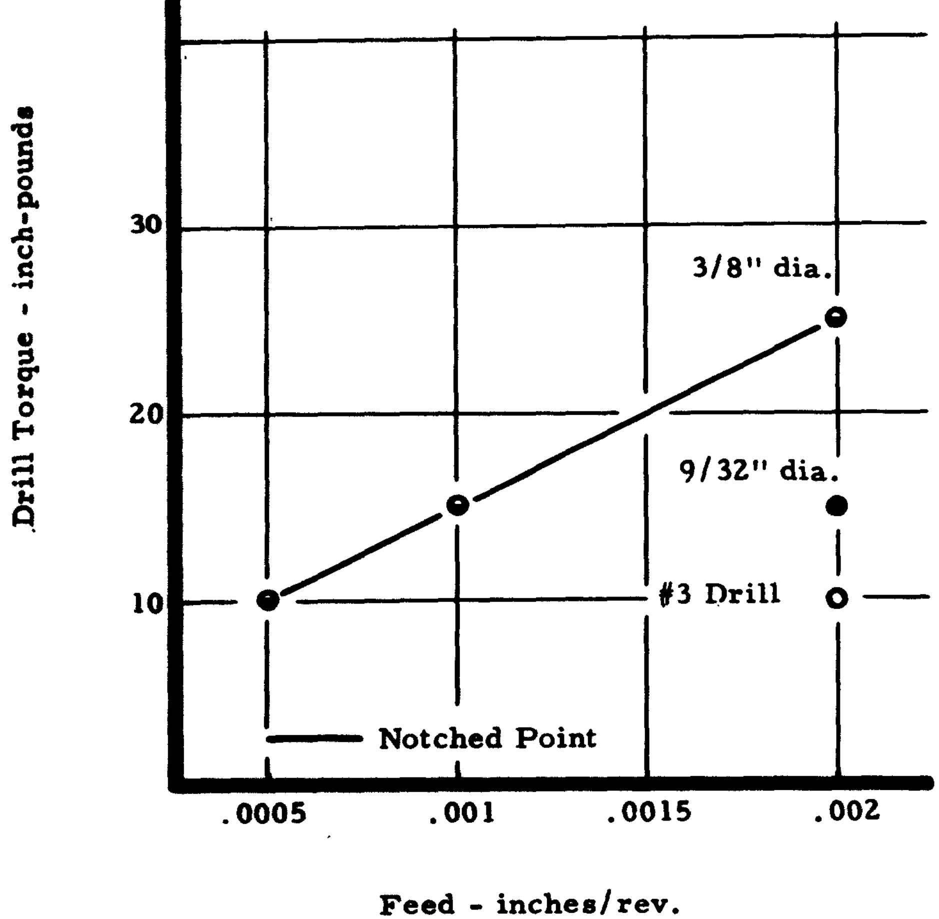


See Text page 30

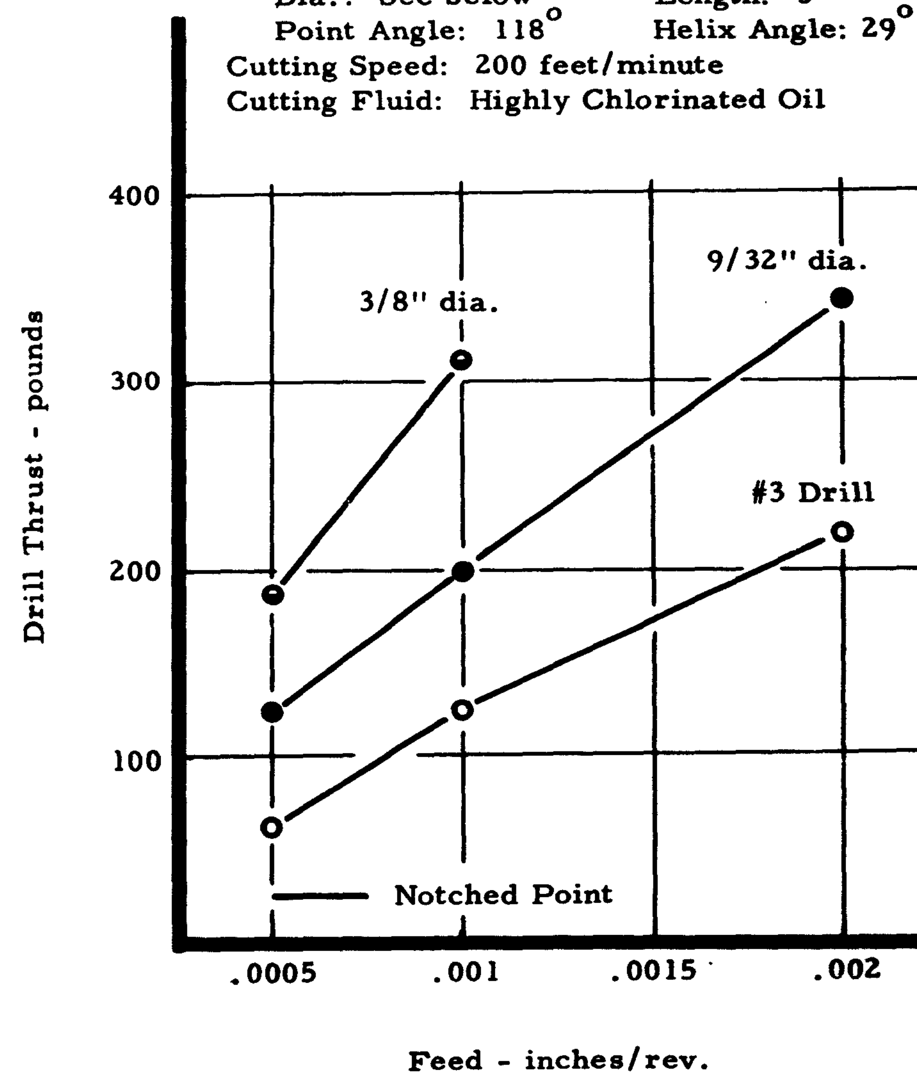
Figure 66

Drilling Forged Tungsten
Drill Torque and Drill Thrust

Drill: Grade 883 (C-2) Carbide
Dia.: See below   Length: 3"
Point Angle: 118°   Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil



Drill: Grade 883 (C-2) Carbide
Dia.: See below   Length: 3"
Point Angle: 118°   Helix Angle: 29°
Cutting Speed: 200 feet/minute
Cutting Fluid: Highly Chlorinated Oil

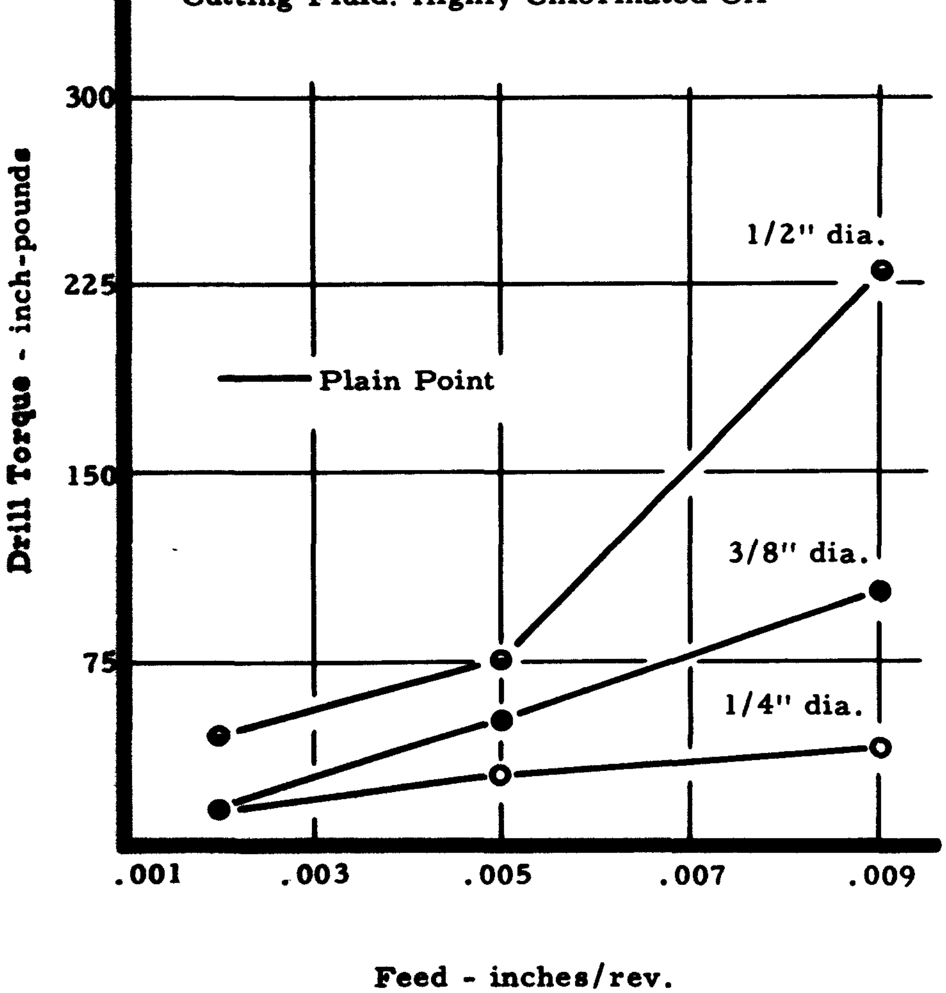


See Text page 30

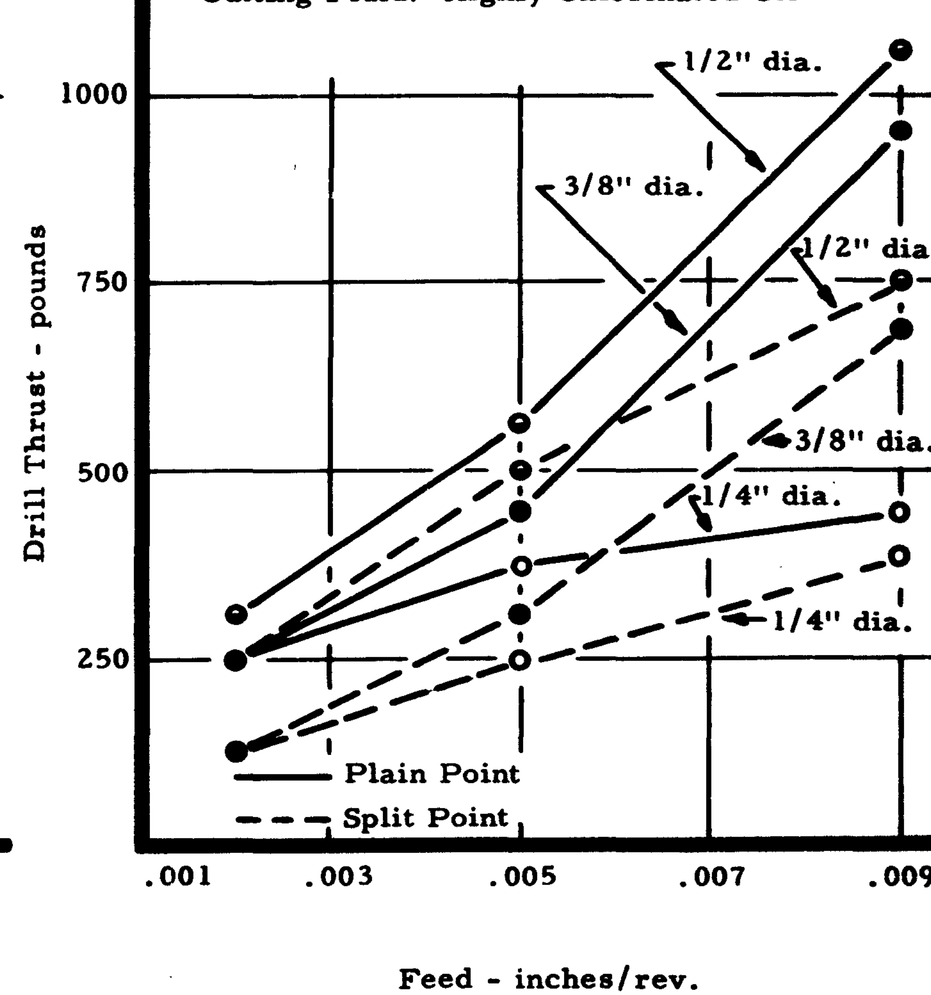
Figure 67

Drilling 90Ta-10W Alloy, 207 BHN
Drill Torque and Drill Thrust

Drill: M-2 HSS
Dia.: See below — Length: 3"
Point Angle: 118° — Helix Angle: 29°
Cutting Speed: 50 feet/minute
Cutting Fluid: Highly Chlorinated Oil



Drill: M-2 HSS
Dia.: See below — Length: 3"
Point Angle: 118° — Helix Angle: 29°
Cutting Speed: 50 feet/minute
Cutting Fluid: Highly Chlorinated Oil

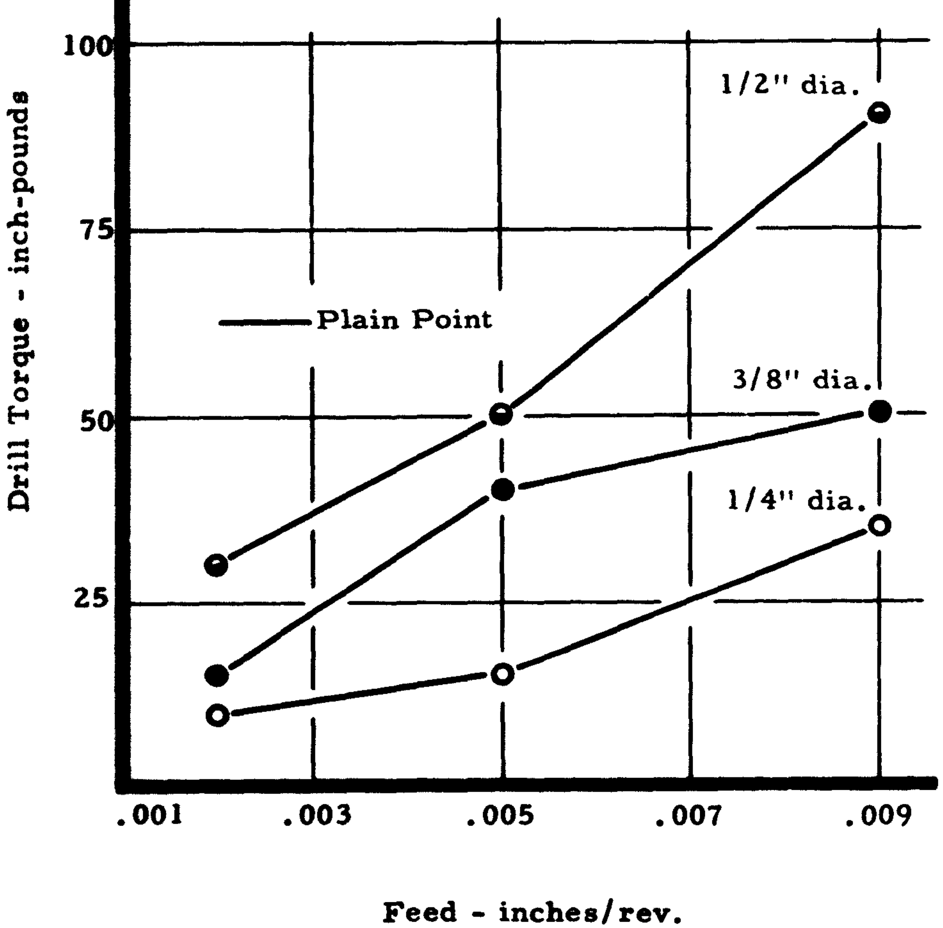


See Text page 30

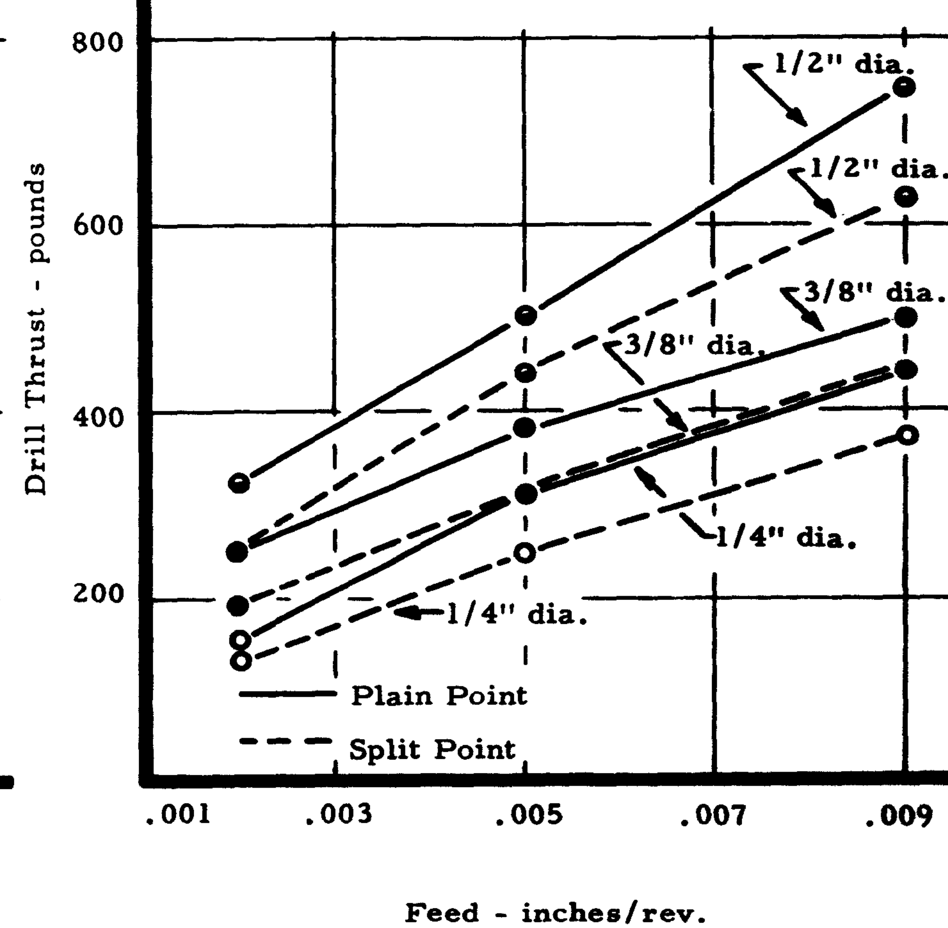
Figure 68

Drilling Columbium D-31, 207 BHN
Drill Torque and Drill Thrust

Drill: M-2 HSS
Dia.: See below   Length: 3"
Point Angle: 118°   Helix Angle: 29°
Cutting Speed: 50 feet/minute
Cutting Fluid: Highly Chlorinated Oil

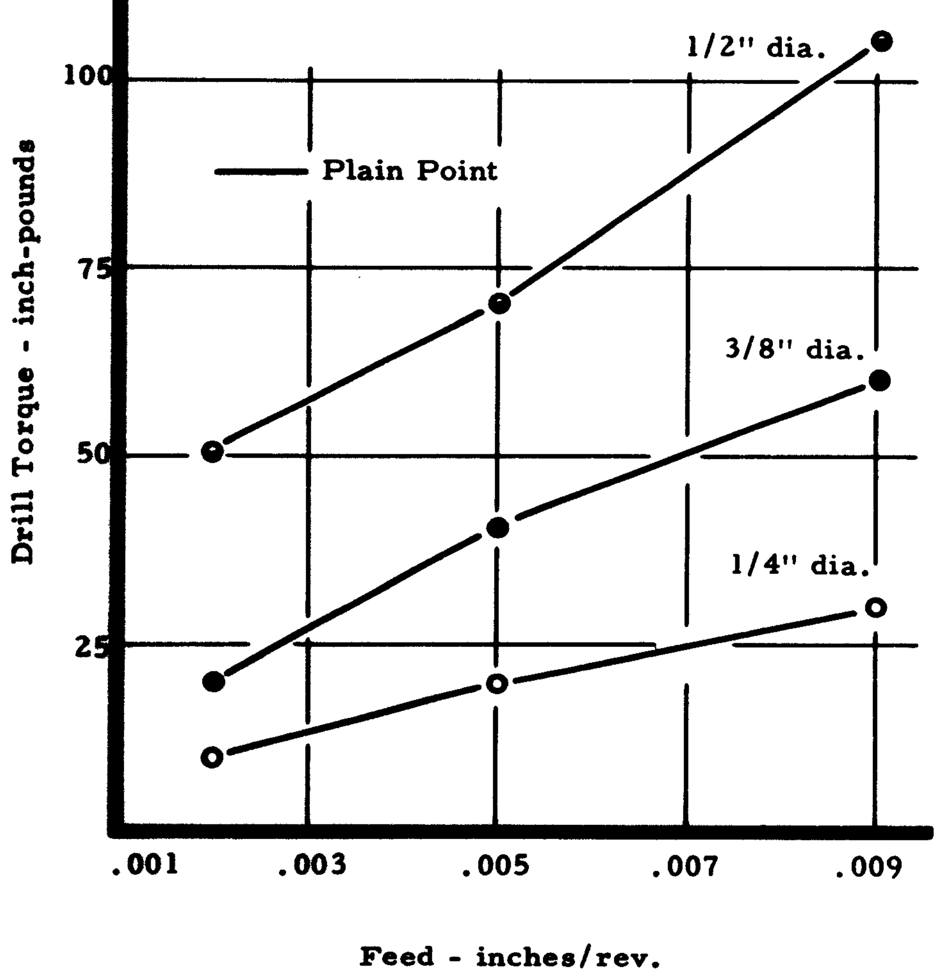


Drill: M-2 HSS
Dia.: See below   Length: 3"
Point Angle: 118°   Helix Angle: 29°
Cutting Speed: 50 feet/minute
Cutting Fluid: Highly Chlorinated Oil

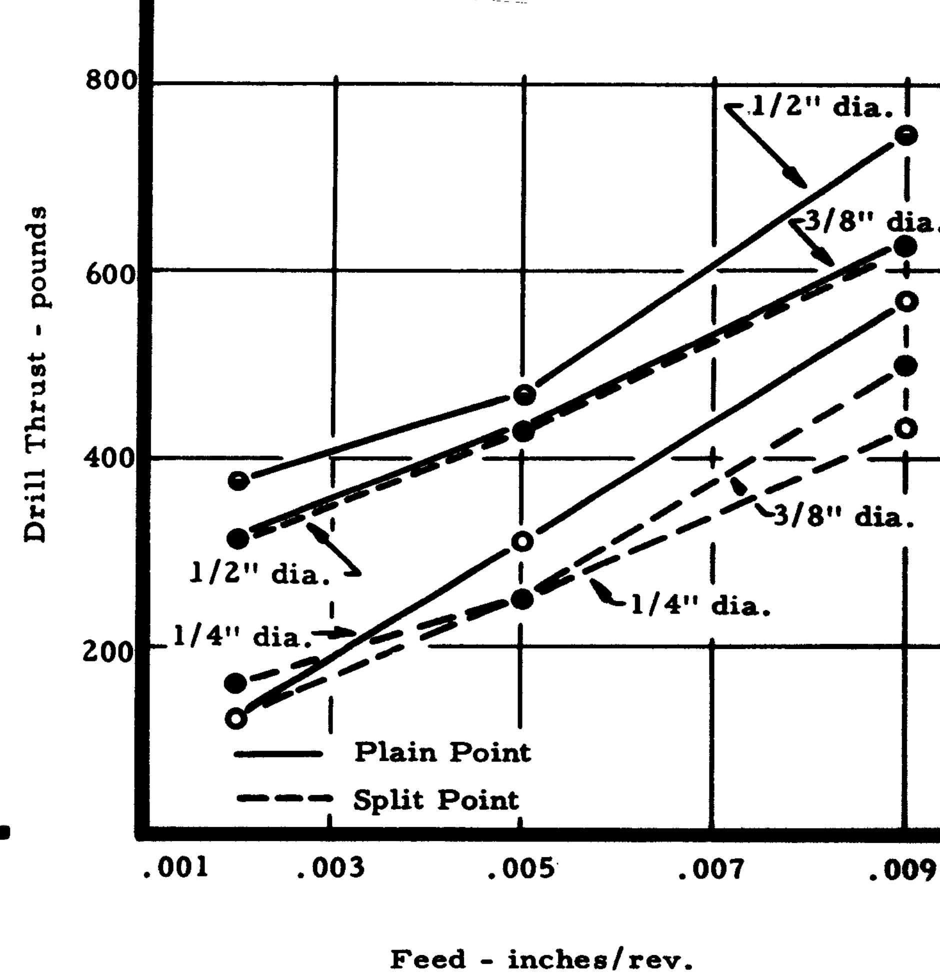


Drilling TZM Molybdenum Alloy, 229 BHN
Drill Torque and Drill Thrust

Drill: M-2 HSS
Dia.: See below — Length: 3"
Point Angle: 118° — Helix Angle: 29°
Cutting Speed: 100 feet/minute
Cutting Fluid: Highly Chlorinated Oil



Drill: M-2 HSS
Dia.: See below — Length: 3"
Point Angle: 118° — Helix Angle: 29°
Cutting Speed: 100 feet/minute
Cutting Fluid: Highly Chlorinated Oil



See Text page 30

Figure 70

TABLE 2

AVERAGE UNIT POWER REQUIRED FOR DRILLING REFRACTORY ALLOYS

Drill Dia.: See below | Point Grind: Plain and Notched | Cutting Fluid: Highly Chlorinated Oil

Drill Material: HSS and Carbide | Clearance Angle: 5°

Point Angle: 118° | Helix Angle: 29°

Work Material	Drill Dia.	Feed Range in./rev.	Cutting Speed ft./min.	Average Unit Power hp/cu.in./min.
Pressed & Sintered	#3	.0005-.002	200	2.20
Tungsten, 95% Density	9/32"	.0005-.002	200	2.12
34 R_c	3/8"	.0005-.002	200	2.50
Arc Cast Tungsten,	#3	.0005-.002	200	2.20
99% Density, 31 R_c	9/32"	.0005-.002	200	2.24
	3/8"	.0005-.002	200	2.28
Forged Tungsten,	#3	.0005-.002	200	2.20
96% Density, 35 R_c	9/32"	.0005-.002	200	2.20
	3/8"	.0005-.002	200	2.28
D-31 Columbium,	1/4"	.002-.009	50	1.27
217 BHN	3/8"	.002-.009	50	1.01
	1/2"	.002-.009	50	0.94
90Ta-10W Alloy,	1/4"	..002-.009	50	1.94
207 BHN	3/8"	.002-.009	50	1.37
	1/2"	.002-.009	50	1.33
TZM Molybdenum,	1/4"	.002-.009	100	1.28
229 BHN	3/8"	.002-.009	100	1.18
	1/2"	.002-.009	100	1.35
D6AC Steel,	#3	.0005-.002	150	2.10
Q & T, 56 R_c	9/32"	.0005-.002	150	2.12
	3/8"	.0005-.002	150	2.03

TABLE 3

AVERAGE UNIT POWER AND COEFFICIENT OF FRICTION FOR TURNING REFRACTORY ALLOYS

Tool Material: Carbide — Cutting Fluid: None

Tool Geometry: See below — Depth of Cut: .100"

Work Material	Tool Geometry	Feed Range in./rev.	Cutting Speed ft./min.	Average Coefficient of Friction	Average Unit Power hp/cu.in./min.
Pressed & Sintered Tungsten, 95% Density 34 R_c	BR: -15°, SR: 0°	.005-.015	200	.50	1.98
	BR: -15°, SR: -5°	.005-.015	200	.44	2.33
	BR: -15°, SR: -10°	.005-.015	200	.37	2.64
Arc Cast Tungsten, 99% Density, 31 R_c	BR: -15°, SR: 0°	.005-.015	200	.44	2.05
	BR: -15°, SR: -5°	.005-.015	200	.36	2.62
	BR: -15°, SR: -10°	.005-.015	200	.37	2.63
TZM Molybdenum, 229 BHN	BR: 0°, SR: 20°	.005-.015	450	.83	1.46
	BR: 0°, SR: 10°	.005-.015	450	.55	1.62
	BR: 0°, SR: 0°	.005-.015	450	.48	2.52
D-31 Columbium, 217 BHN	BR: 0°, SR: 20°	.005-.015	300	.80	1.18
	BR: 0°, SR: 10°	.005-.015	300	.63	1.39
	BR: 0°, SR: 0°	.005-.015	300	.58	1.44
90Ta-10W Alloy, 207 BHN	BR: 0°, SR: 20°	.005-.015	150	.79	1.59
	BR: 0°, SR: 10°	.005-.015	150	.80	2.37
	BR: 0°, SR: 0°	.005-.015	150	.77	3.01

TABLE 3 (continued)

AVERAGE UNIT POWER AND COEFFICIENT OF FRICTION FOR TURNING REFRACTORY ALLOYS

Work Material	Tool Geometry	Feed Range in./rev.	Cutting Speed ft./min.	Average Coefficient of Friction	Average Unit Power hp/cu. in./min.
Rene 41, Sol. Tr. 320 BHN	BR: 0°, SR: 10°	.005-.015	50	.54	2.11
	BR: 0°, SR: 5°	.005-.015	50	.51	2.38
	BR: -5°, SR: -5°	.005-.015	50	.50	2.84
Rene 41, Sol. Tr. & Aged, 365 BHN	BR: 0°, SR: 10°	.005-.015	50	.68	2.43
	BR: 0°, SR: 5°	.005-.015	50	.54	2.83
	BR: -5°, SR: -5°	.005-.015	50	.42	3.01
D6AC Steel, Q & T 56 R_c	BR: 0°, SR: 0°	.005-.015	75	.47	2.70
	BR: -5°, SR: 0°	.005-.015	75	.48	2.95
	BR: -15°, SR: 0°	.005-.015	75	.44	2.97

APPENDIX A

HARDNESS NUMBER CONVERSION FOR STEELS*

Hardness		Tensile Strength	Hardness		Tensile Strength
Brinell**	Rockwell C	X1000 (Approx.)	Brinell**	Rockwell C	X1000 (Approx.)
670	61.0		415	44.5	210
656	60.1		405	43.6	204
647	59.7		397	42.7	200
638	59.2	329	388	41.8	195
630	58.8	324	379	40.8	190
620	58.3	319	369	39.8	185
611	57.8	314	360	38.8	180
601	57.3	309	350	37.7	175
591	56.8	304	341	36.6	170
582	56.3	299	331	35.5	166
573	55.7	294	322	34.4	161
564	55.2	289	313	33.3	156
554	54.7	284	303	32.2	151
545	54.1	279	294	31.0	146
535	53.6	274	284	29.8	141
525	53.0	269	280	29.2	139
517	52.3	264	275	28.5	136
507	51.7	260	270	27.8	134
497	51.1	254	265	27.1	131
488	50.5	250	261	26.4	129
479	49.8	244	256	25.6	126
471	49.1	240	252	24.8	124
460	48.4	234	247	24.0	121
452	47.7	230	243	23.1	119
442	46.9	224	238	22.2	116
433	46.1	220	233	21.3	114
425	45.3	214	228	20.3	111

* Taken from SAE Handbook, 1961

** Brinell hardness measurements taken using a 3000 Kg load - 10 mm carbide ball.

APPENDIX B

CUTTING TOOL MATERIALS

High Speed Steel

Type	Nominal Composition
T-1	18% W, 4% Cr, 1% V
T-15	13% W, 4-1/4% Cr, 5% V, 5% Co
M-1	8% Mo, 4% Cr, 1% V, 1-1/2% W
M-2	5% Mo, 4% Cr, 2% V, 6% W
M-3	6% W, 4% Cr, 3% V, 6% Mo
M-7	1-3/4% W, 3-3/4% Cr, 2% V, 8-3/4% Mo
M-10	8% Mo, 4% Cr, 2% V
M-33	1-3/4% W, 3-3/4% Cr, 1% V, 9-3/4% Mo, 8-1/4% Co
Braecut	12% Co, 6-1/4% Mo, 5-1/4% W, 4-1/4% Cr, 2-1/4% V

Cast Alloy

	Nominal Composition
Tantung G	47% Co, 30% Cr, 15% W, 5% Others
Stellite 98 M2	41% Co, 32% Cr, 17% W, 10% Others
Crobalt No. 2	40% Co, 33% Cr, 18% W, 9% Others

Sintered Carbide

Grade	Application
C-1	Roughing Cuts - Severe: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-2	Roughing Cuts - Normal: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-3	Semi-Finish Cuts: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-3	Finishing Cuts: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-4	Precision Finishing: Cast iron, austenitic stainless, titanium, high temperature alloys, non-ferrous alloys
C-5	Roughing Cuts - Severe: Steels (alloy, martensitic, hot work die)
C-6	Roughing Cuts - Normal: Steels (alloy, martensitic, hot work die)
C-7	Semi-Finish Cuts: Steels (alloy, martensitic, hot work die)
C-7	Finish Cuts: Steels (alloy, martensitic, hot work die)
C-8	Precision Finishing: Steels (alloy, martensitic, hot work die)

APPENDIX C

TOOL NOMENCLATURE

TABLE OF EQUIVALENTS

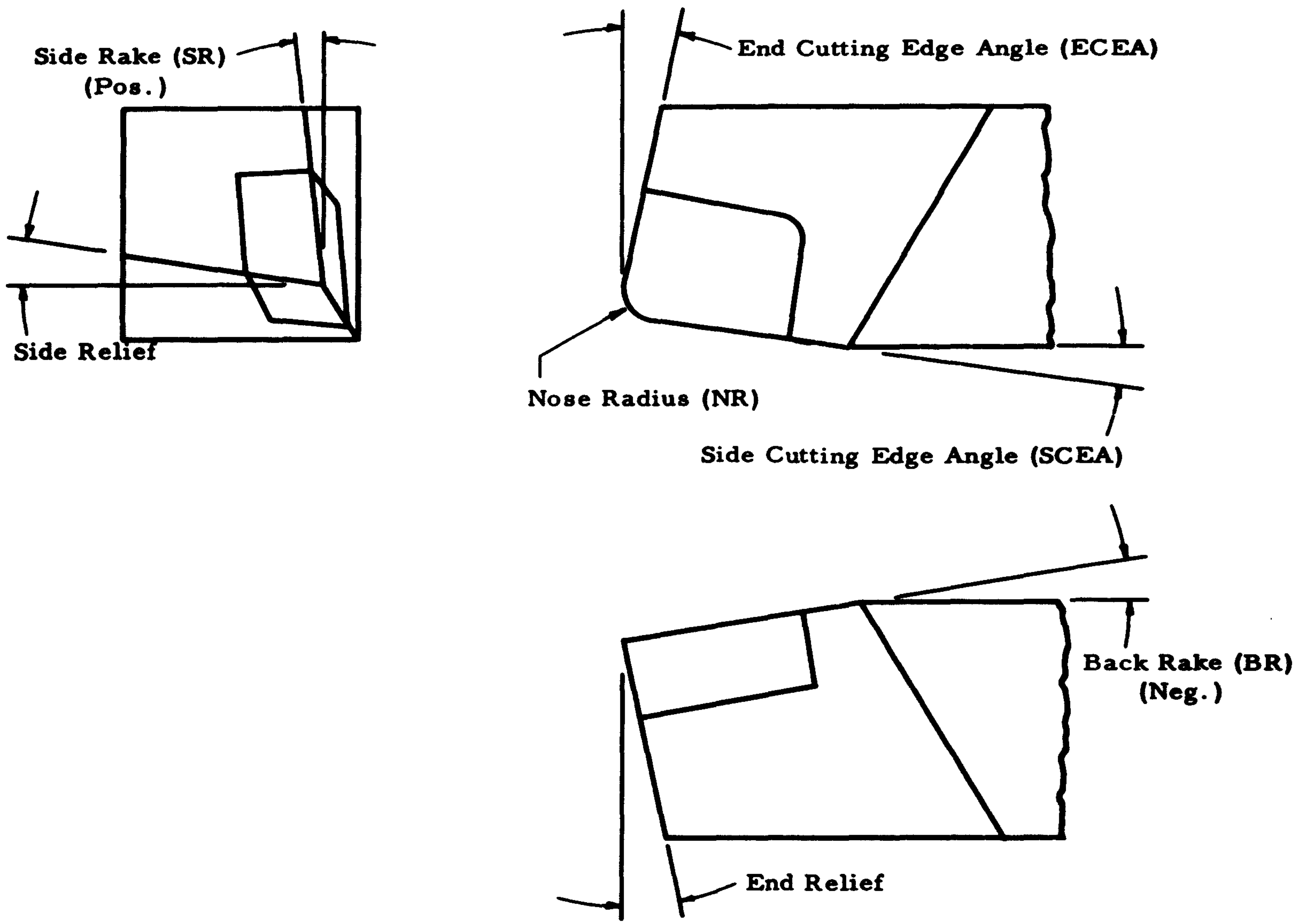
LATHE	MILLING CUTTER	DRILL
Single Point Tools	One Tooth	Approximately Corresponding
	Surfaces	
Tool Face	Tooth Face	Flute Surface
Side Flank	Peripheral Flank	Margin
End Flank	End Flank	Land
	Edges	
Side Cutting Edge	Peripheral Cutting Edge	Margin Edge
End Cutting Edge	End Cutting Edge	Lip
Nose	Tooth Point	No Name
	Angles	
Back Rake	Axial Rake[1]	Helix Angle[1]
Side Rake	Radial Rake	Radial Rake[2]
Side Cutting Edge Angle	Corner Angle	1/2 Point Angle
End Cutting Edge Angle	End Cutting Edge Angle	None
Resultant Rake	Resultant Rake	Resultant Rake
Inclination	Inclination	Inclination
Side Relief	Peripheral Clearance	None
End Relief	End Clearance	Clearance

[1] In any cutting tool whose cutting edge is a helix; e.g., slab mills, reamers, drills, axial rake = inclination = helix angle.

[2] Radial rake in drilling = arc sin web thickness ÷ drill diameter.

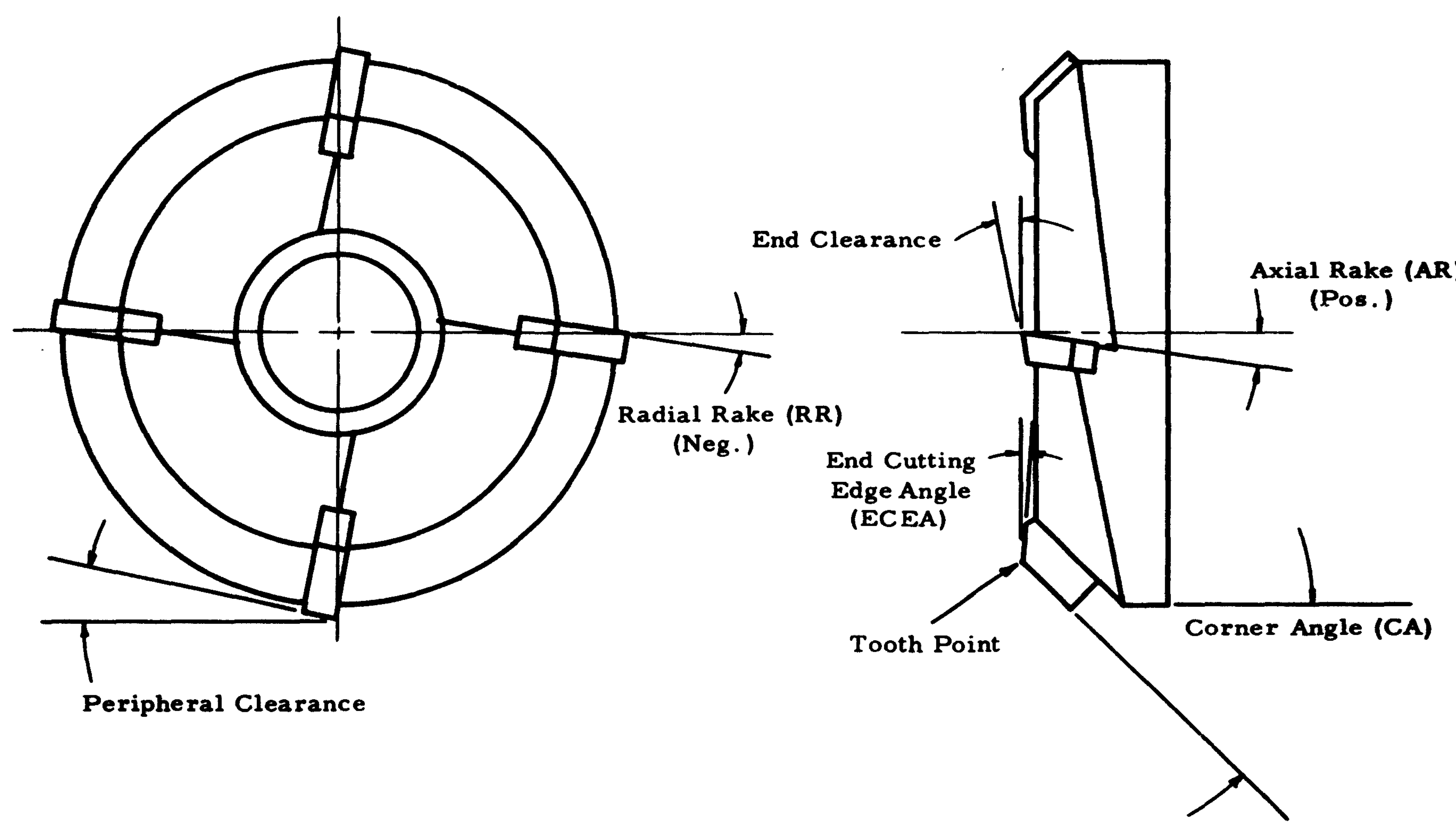
APPENDIX D

Lathe Tool Nomenclature



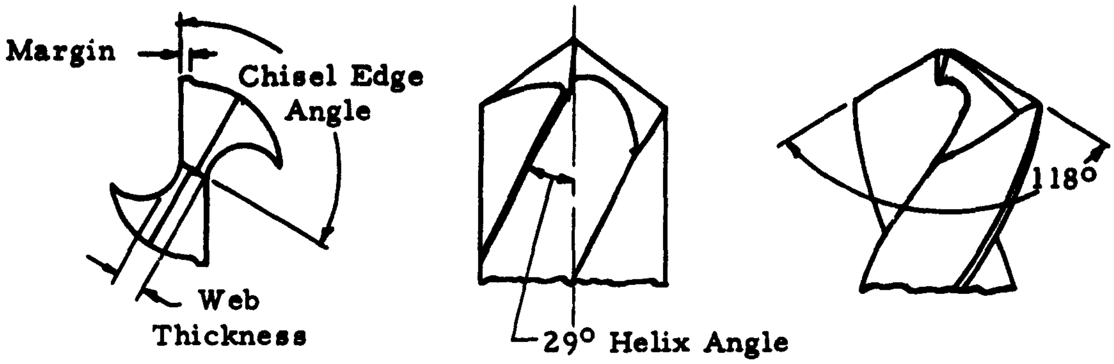
APPENDIX E

Face Mill Nomenclature

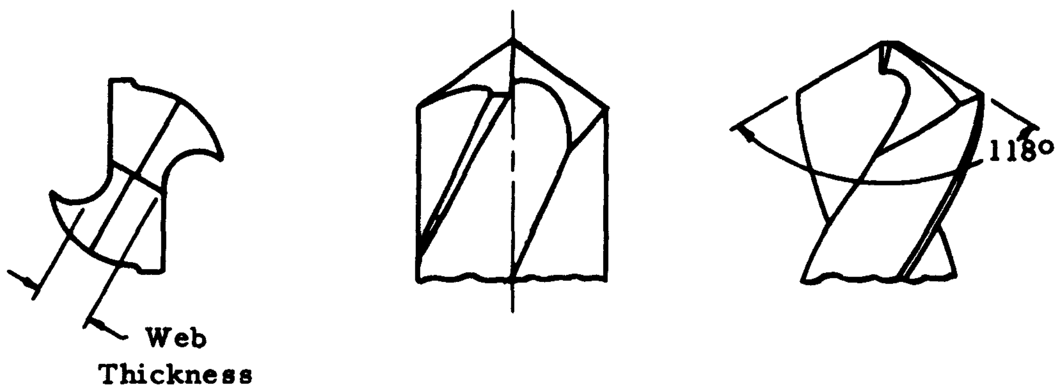


APPENDIX F

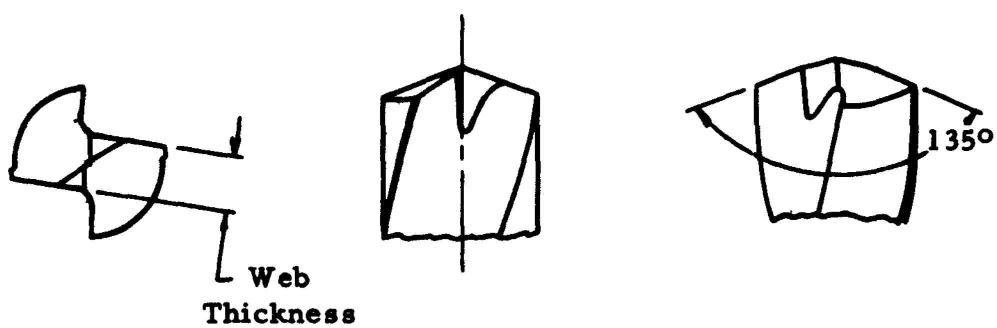
Drill Styles



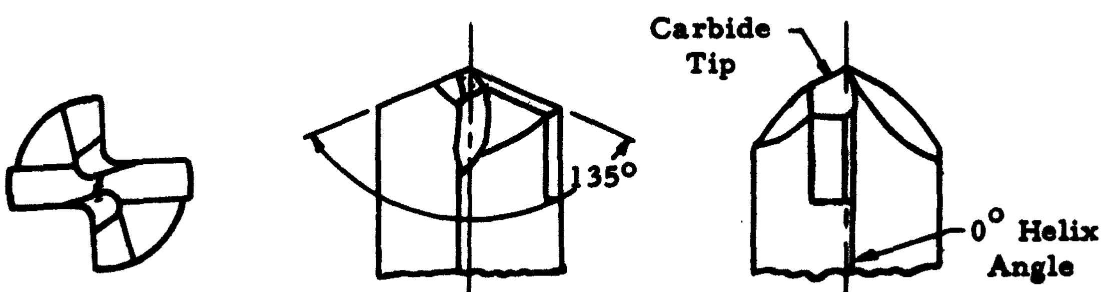
Standard Twist Drill - 29° Helix, Split Point



Heavy Web Drill - 29° Helix, Split Point



Heavy Web Drill - 12° Low Helix, Notched Point



Carbide Tipped Die Drill - 0° Helix, Notched Point

Mechanical Construction for Above Drills in Appendix G

APPENDIX G

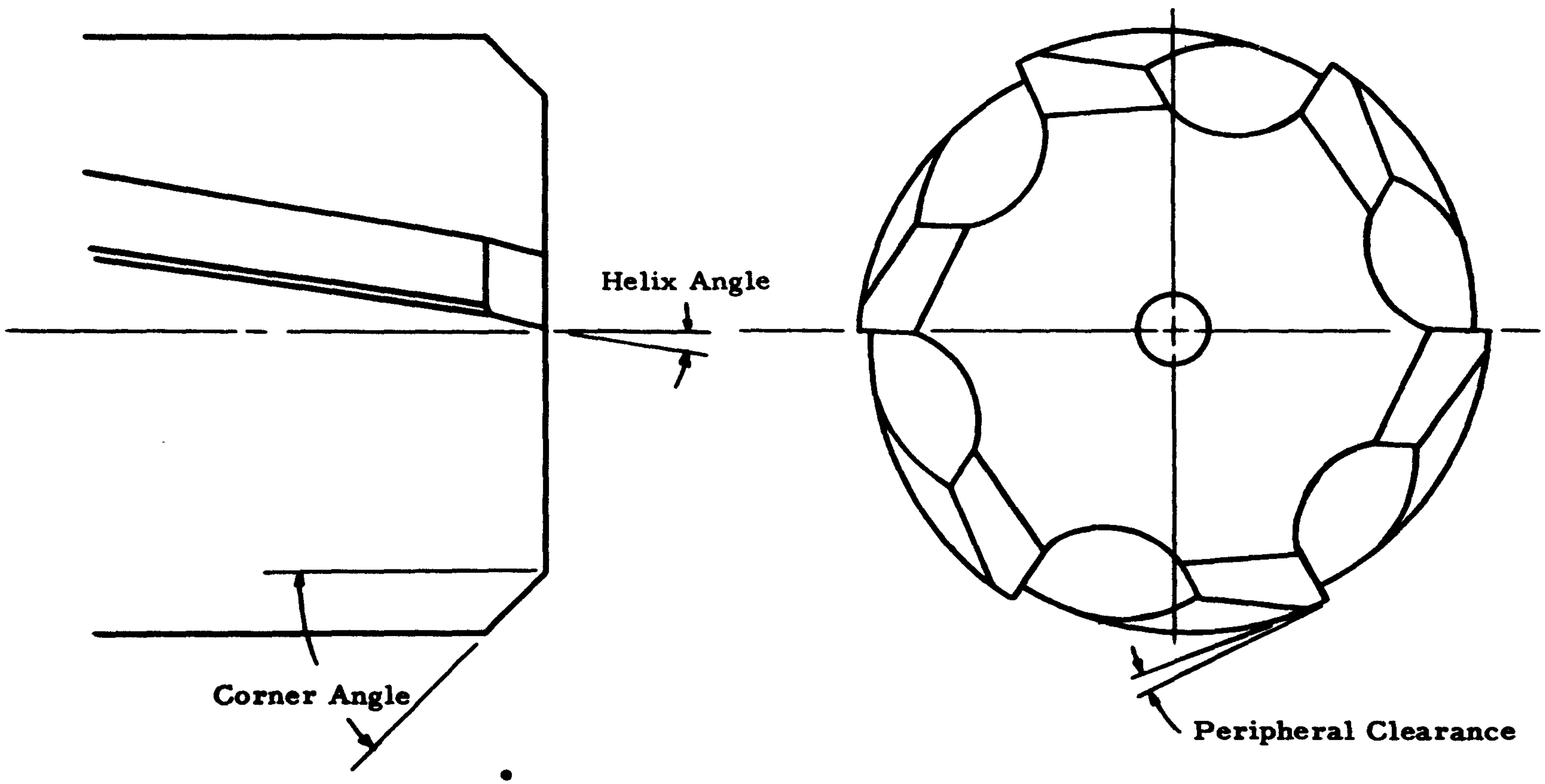
MECHANICAL CONSTRUCTION OF TEST DRILLS

Drill Style	Dia. (in.)	Length: Overall (in.)	Length: Flute (in.)	Helix Angle (degrees)	Web Thickness: At Point (% of dia.)	Web Thickness: Increase (in./in.)
Standard Twist Drill	.250	2-1/2	1-3/8	29	17	.025
Low Helix (12°) Heavy Web Drill	.250	2-1/2*	1	12	32	.026
Regular Helix (29°) Heavy Web Drill	.250	2-1/2*	1	29	40	.026
Carbide Tipped Die Drill	.250	4	2	0	36	.000
Regular Helix (29°) Solid Carbide Drill	.250	4	2-1/2	29	35	.000

* These drills were originally 4" long; the shank end was cut off to produce the stated length.

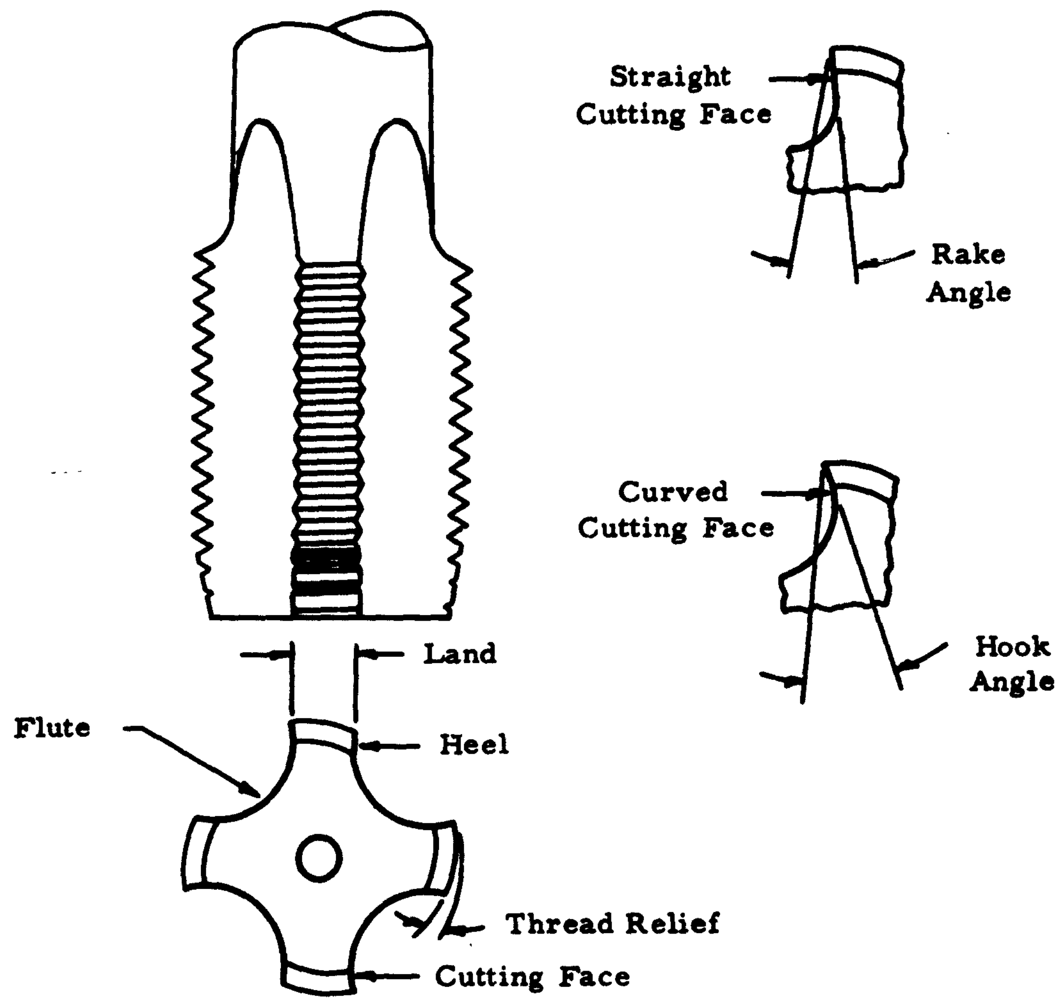
APPENDIX H

Reamer Nomenclature



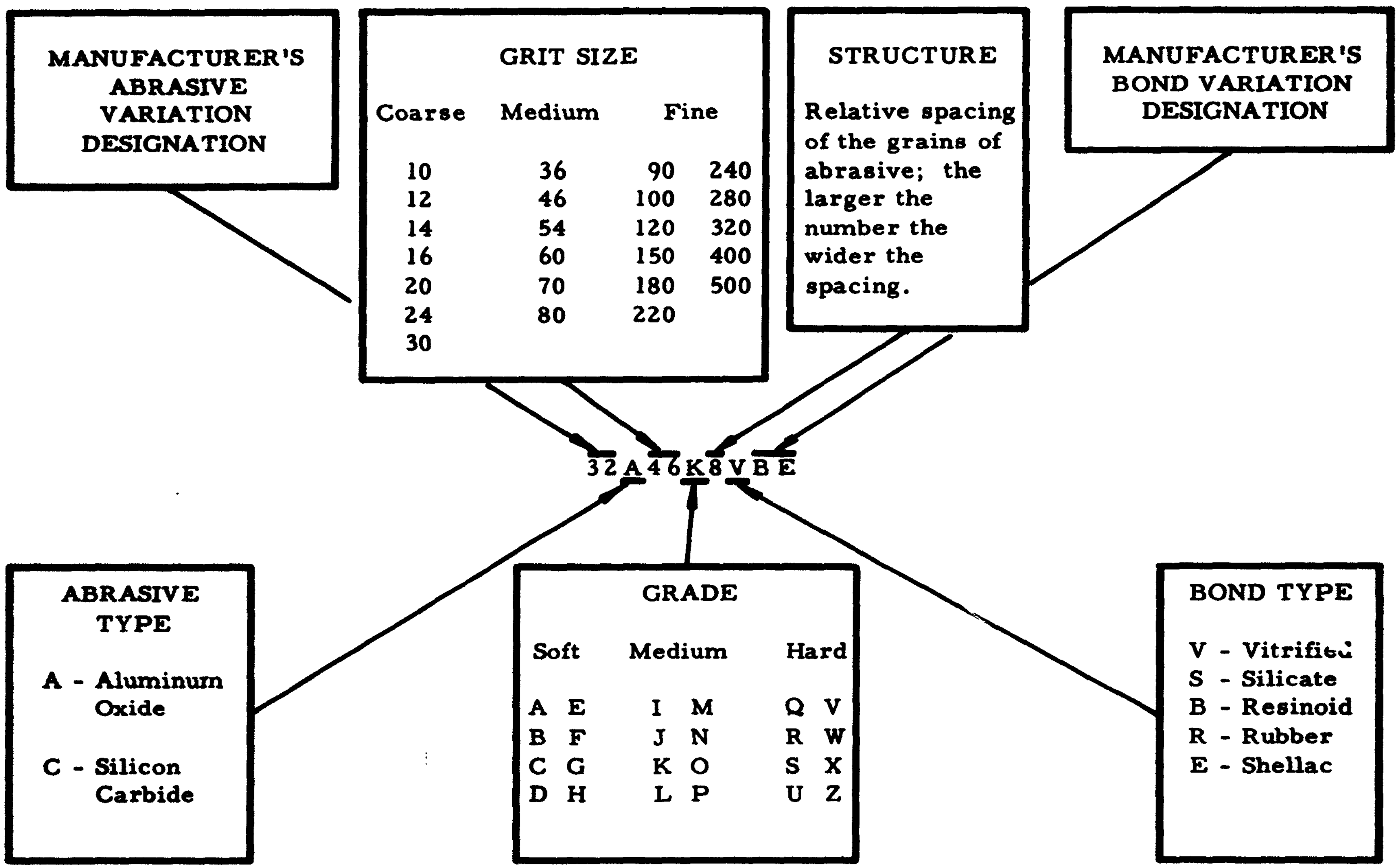
APPENDIX I

Tap Nomenclature



APPENDIX J

GRINDING WHEEL MARKING



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